Hydraulic Fractures, Acoustic Emissions and Shearing

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Norman, July 21, 2011

University of Oklahoma
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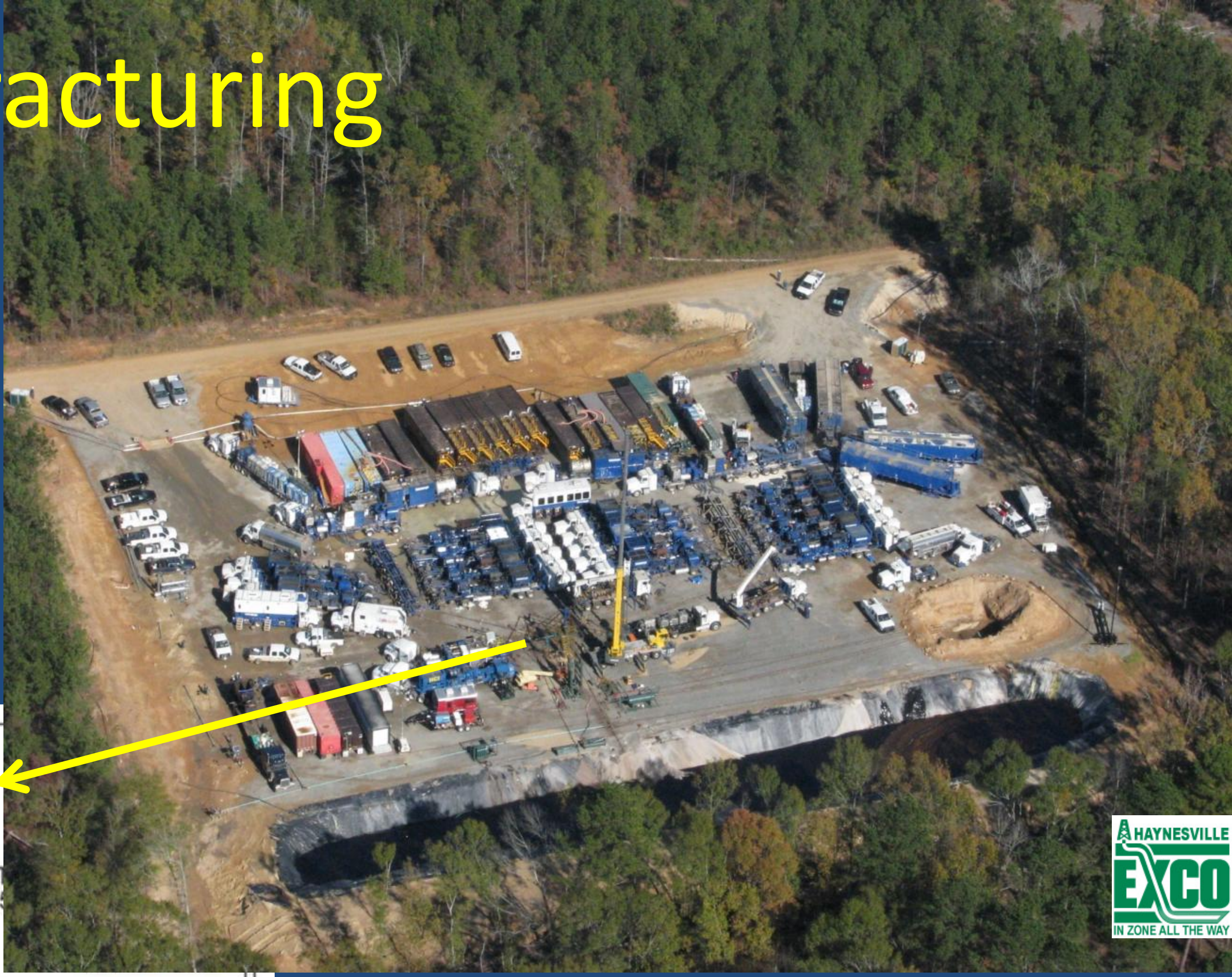
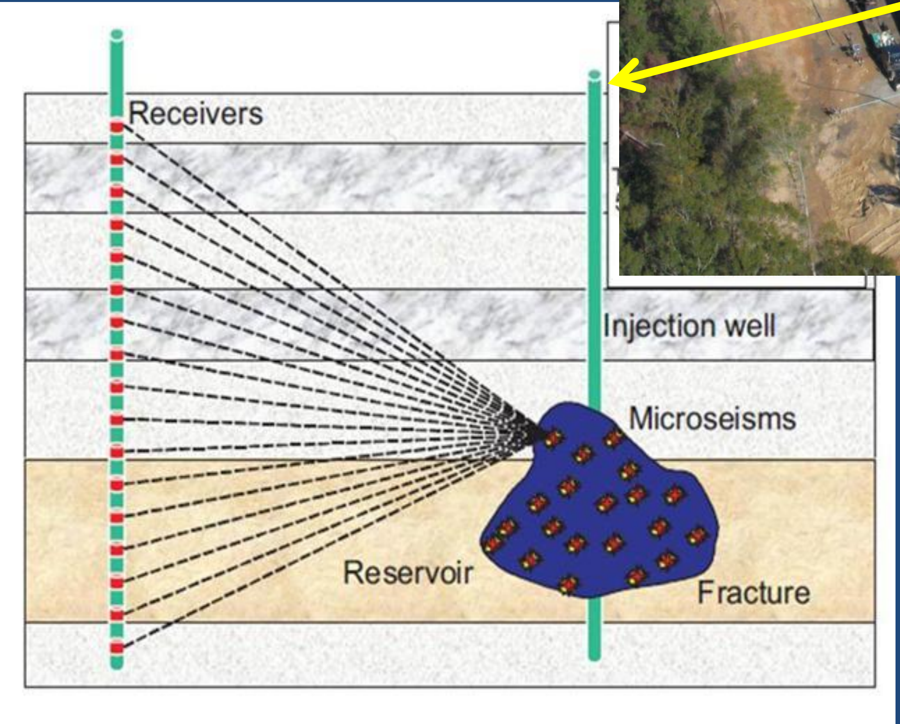
Norman, OK, USA

Hydraulic Fracturing





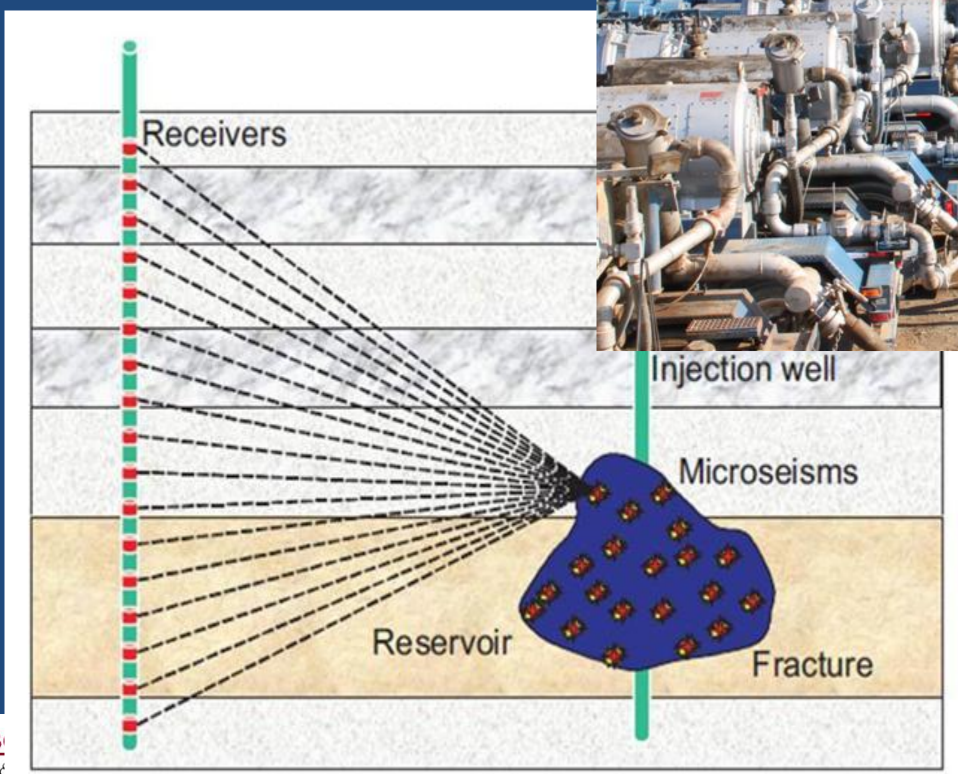
Warpinski (2009)

Field setup

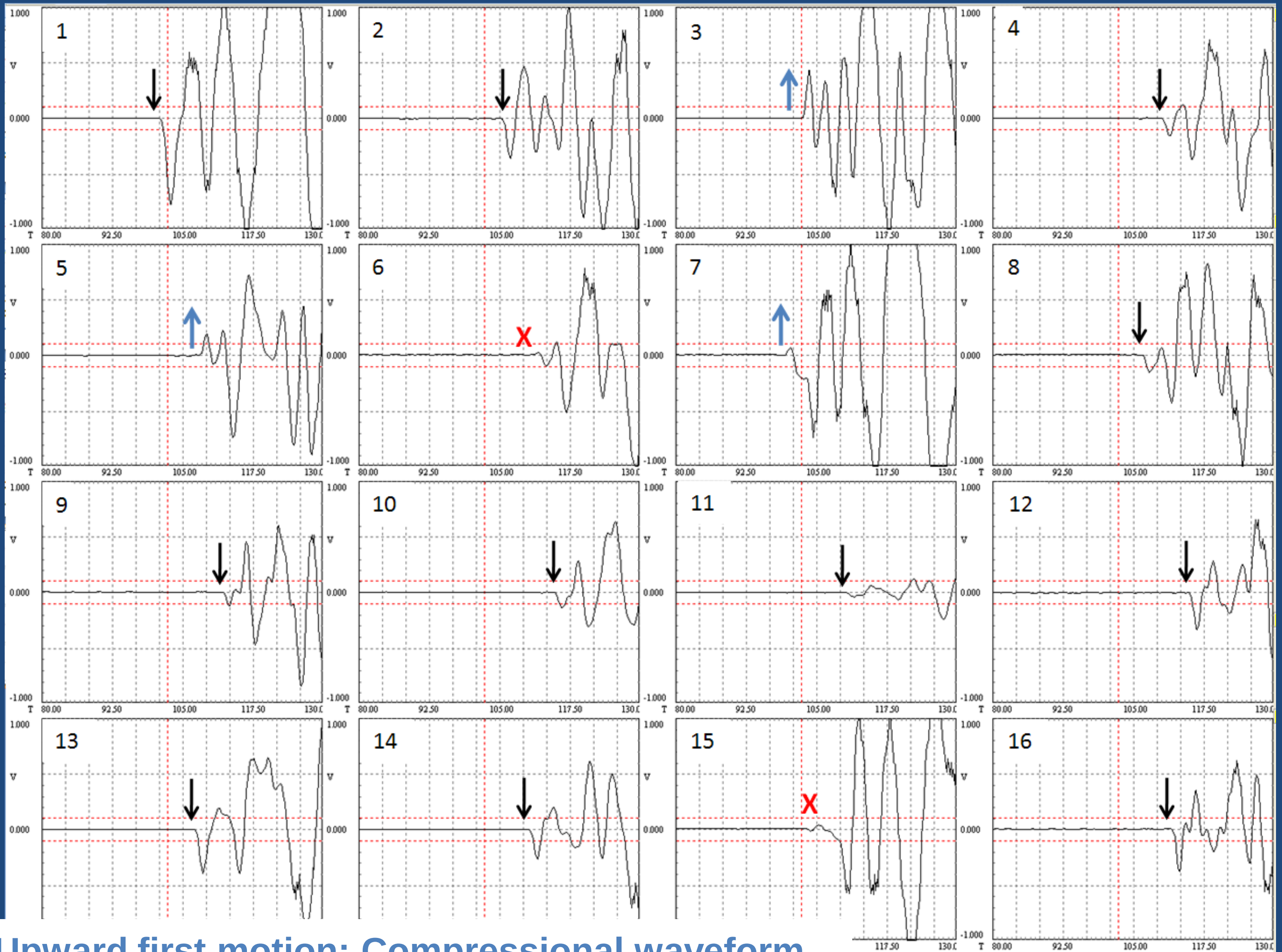
•16 piezoelectric sensors

•Frequency response:50 KHz- 2 MH

•Sampling rate: 5 MHz



Waveforms



Upward first motion: Compressional waveform

Downward first motion: Dilatational waveform

sandstone: event # 4

SPE-138441

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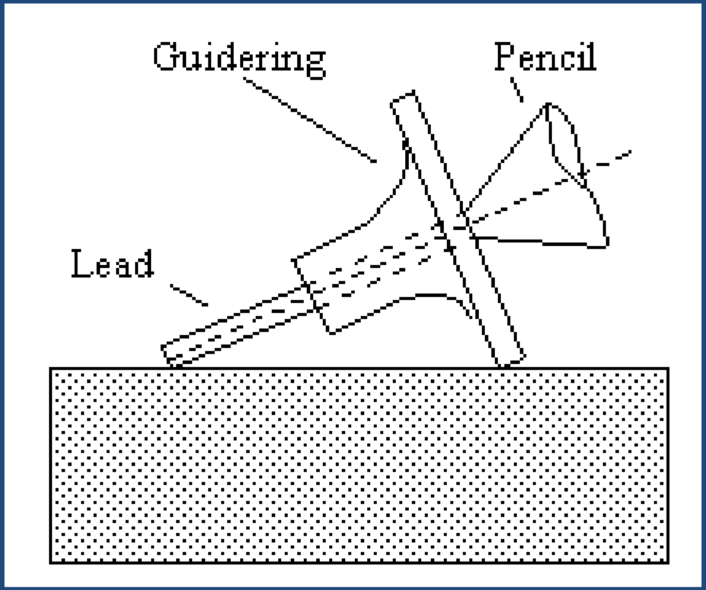
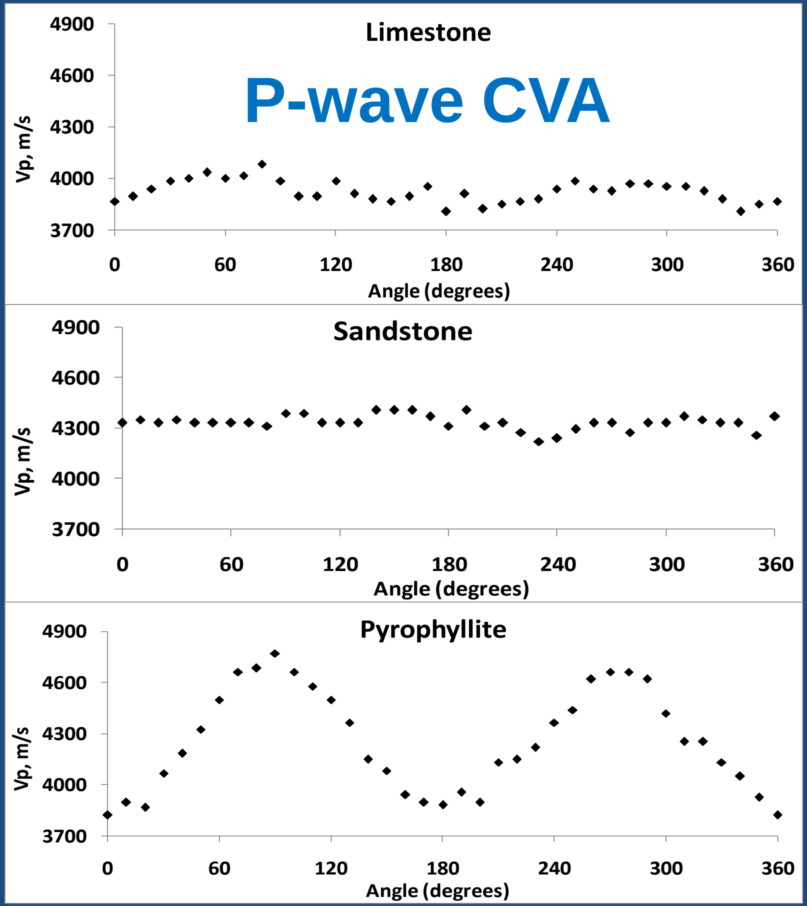
AE Calibration



Hsu and Breckenridge (1981)



Sample	Mineralogy, wgt%	Model	VP (m/sec)	|error | (mm)
Indiana Limestone	Calcite, 95	Constant velocity model	3900	±3.00
Lyons Sandstone	Quartz, 85	Constant velocity model	4335	±3.22
Syn-Shale		Anisotropic model (Berryman 2008)	4300	±6.00
			Anisotropic parameters: ε=0.25, γ= 0.74, δ=0.40	

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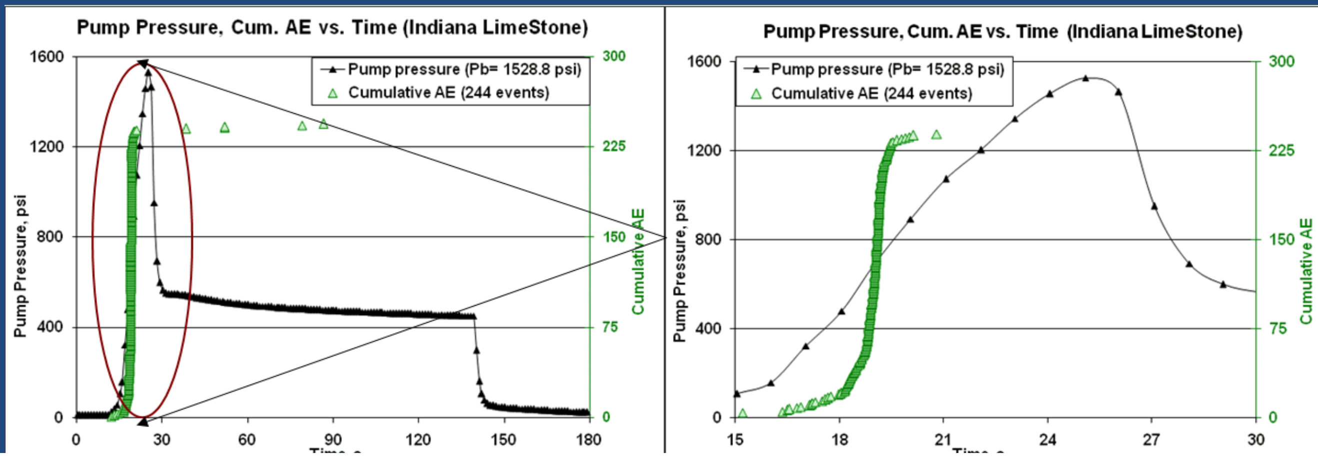
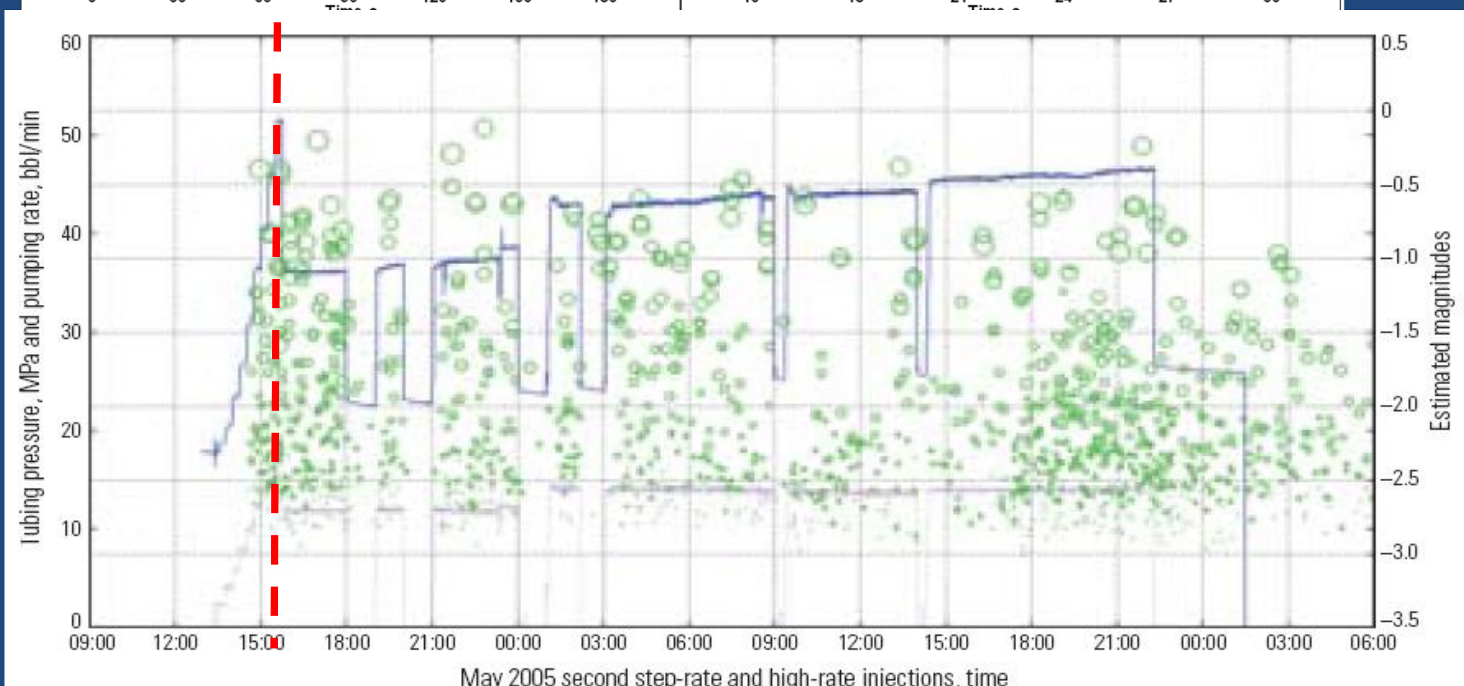
Indiana Limestone: k= 5 md; 3-samps



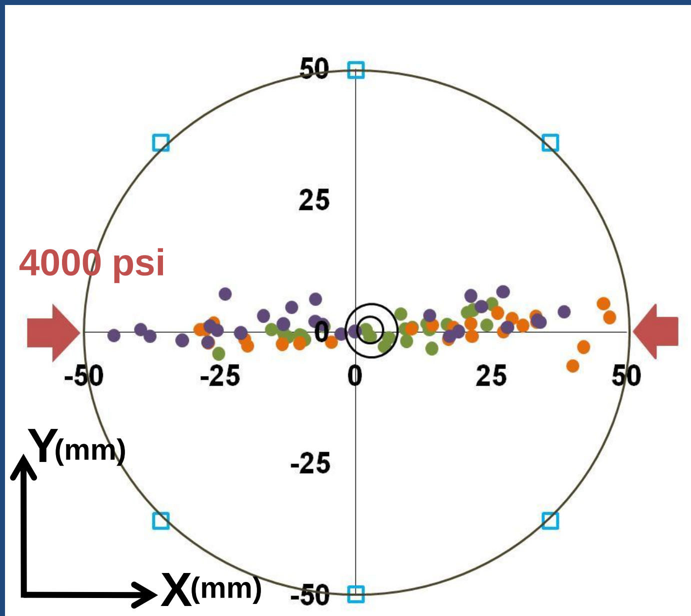
Pump rate=15 cc/min

P_{bdwn} = 1529 psi

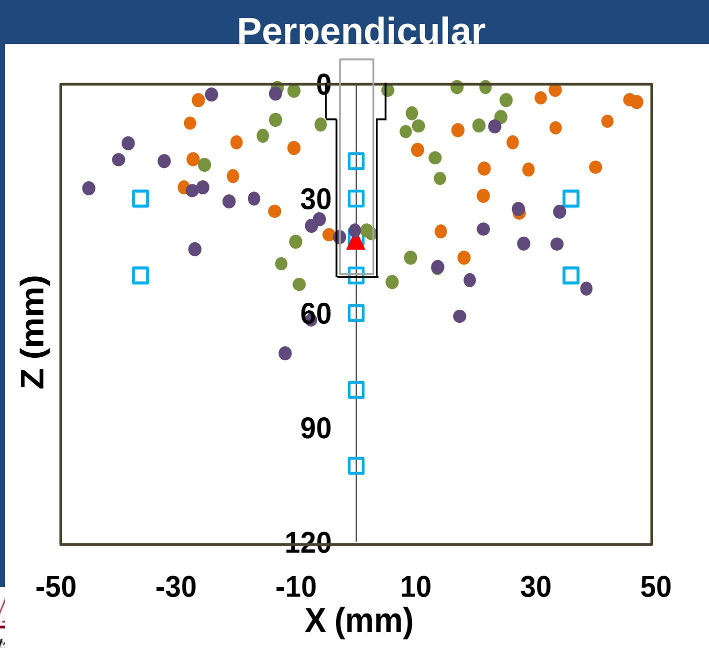
Total 244 events

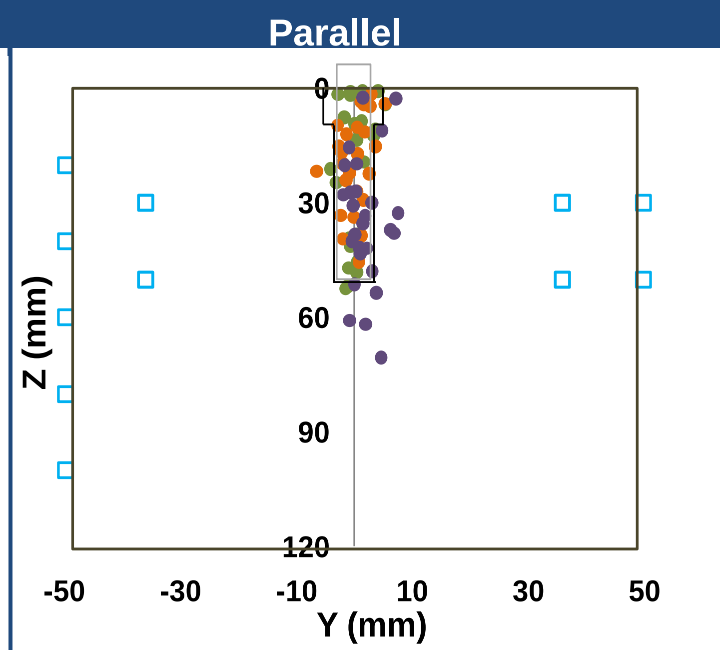


Indiana Limestone: isotropic velocity model



- Fracture aligned with stress direction
- Spatial and temporal propagation of fracture observed (color coding)
- Well developed nearly planar fracture





Time

Early
Intermediate
Late

▲ Perforation
□ Sensor

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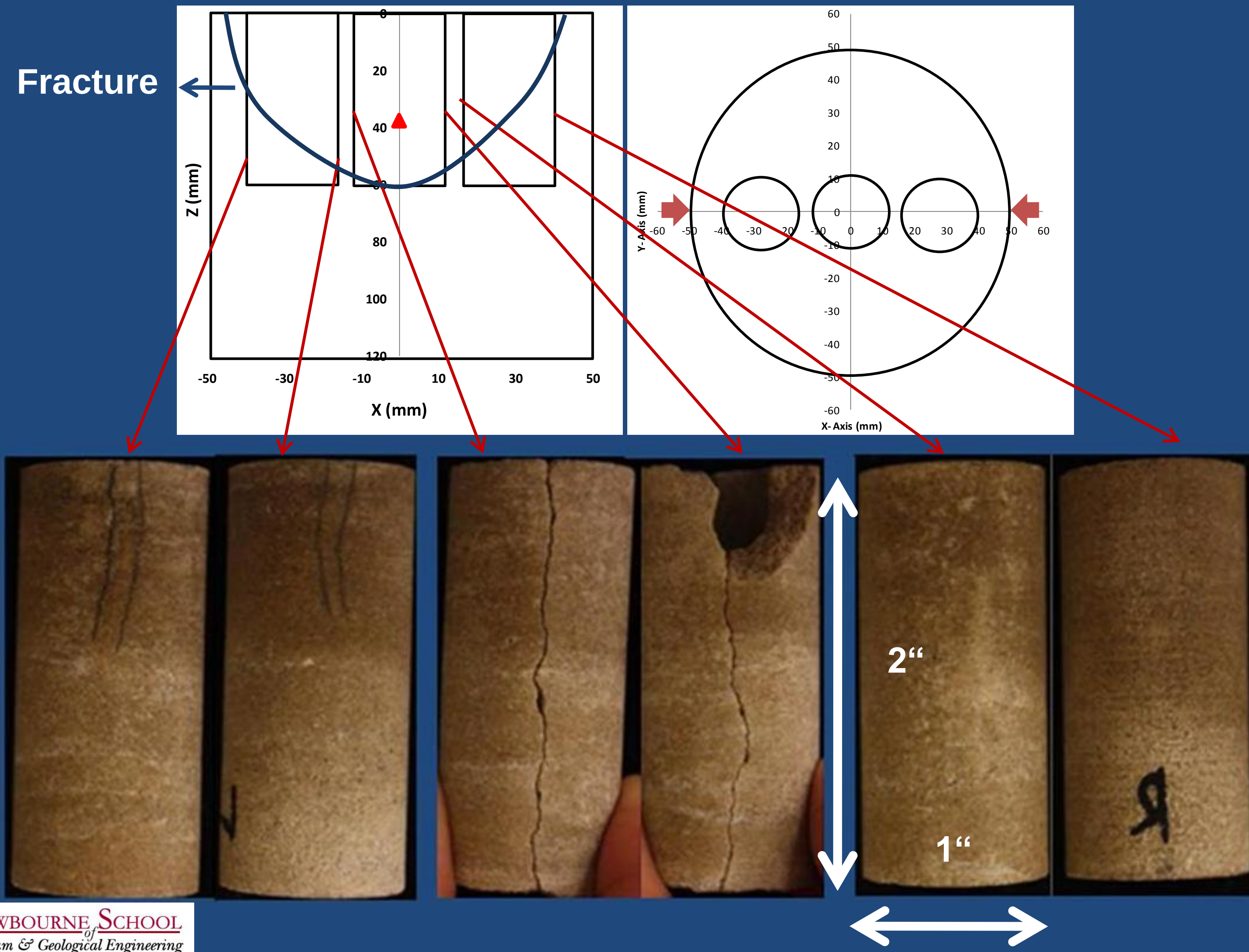
Limestone- Spatial evolution of fractures



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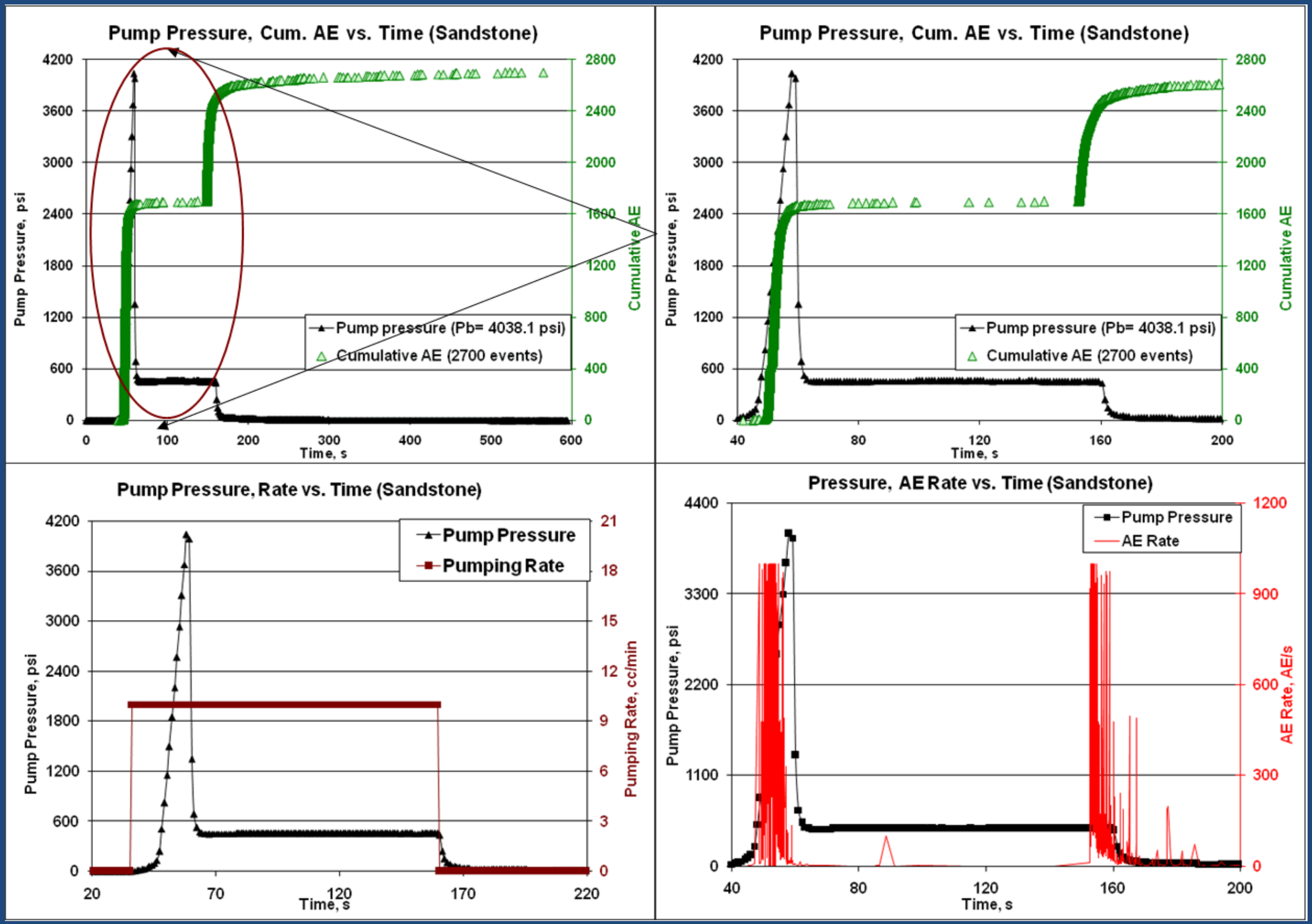
Lyons Sandstone: k=20 μd; ; 8-samps



Pumping rate=10 cc/min

P_{bdwn}= 4038 psi

Total events =2700

- Events occur during pressure build-up and at pump shut-off
- 28% of the recorded events were locatable

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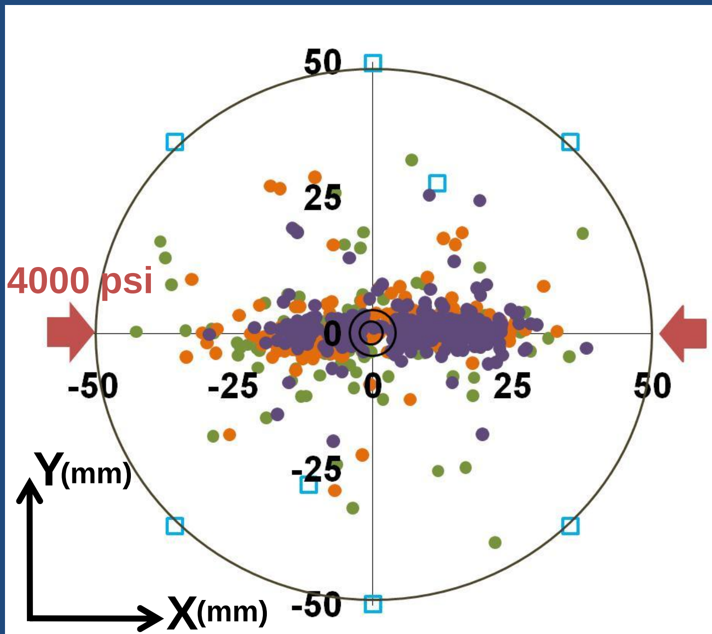
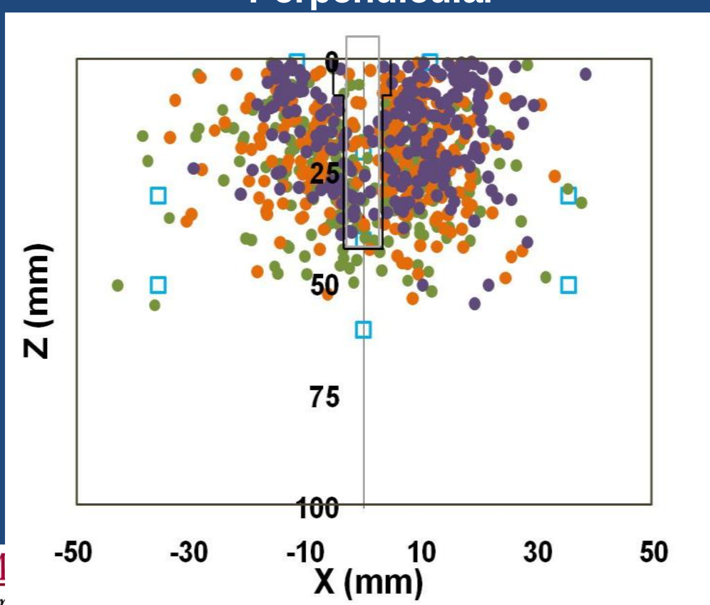
Lyons Sandstone: isotropic velocity model

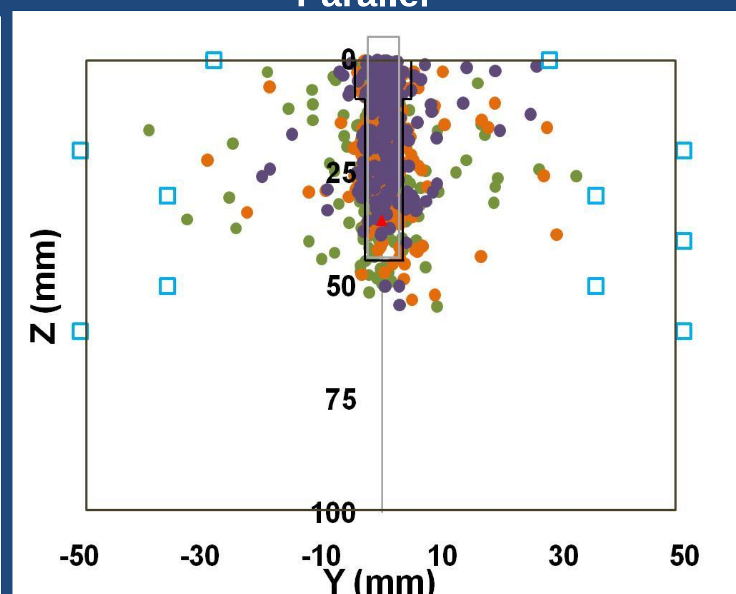


- Fracture aligned with applied stress
- More diffuse distribution of events compared to limestone
- 765 events located

Perpendicular



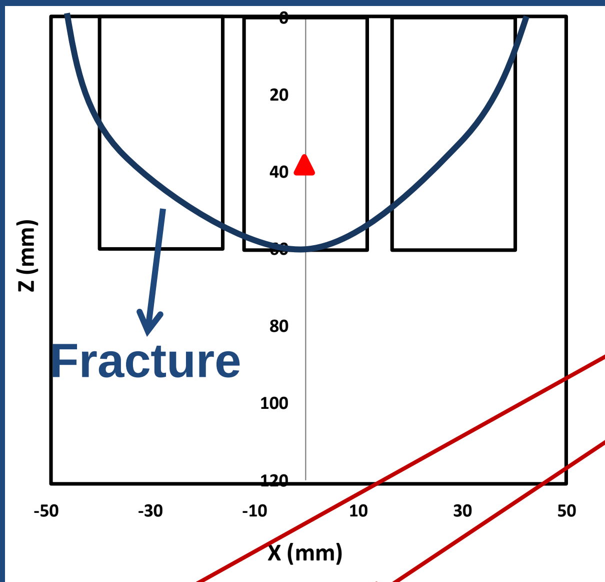
Parallel

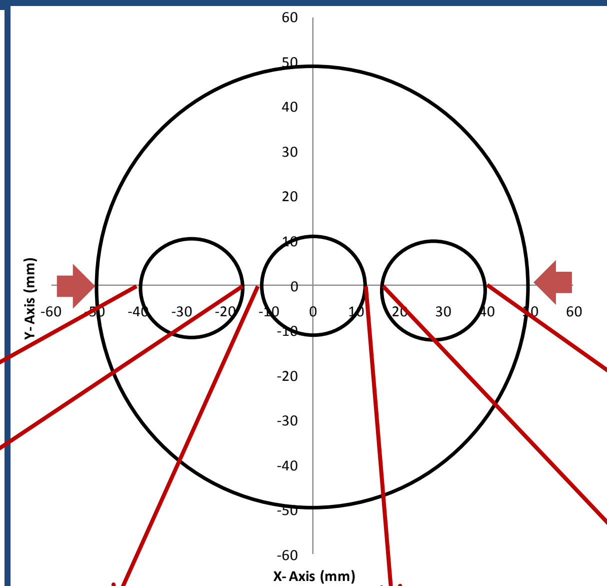


Time
Early
Intermediate
Late

▲ **Perforation**
Sensor

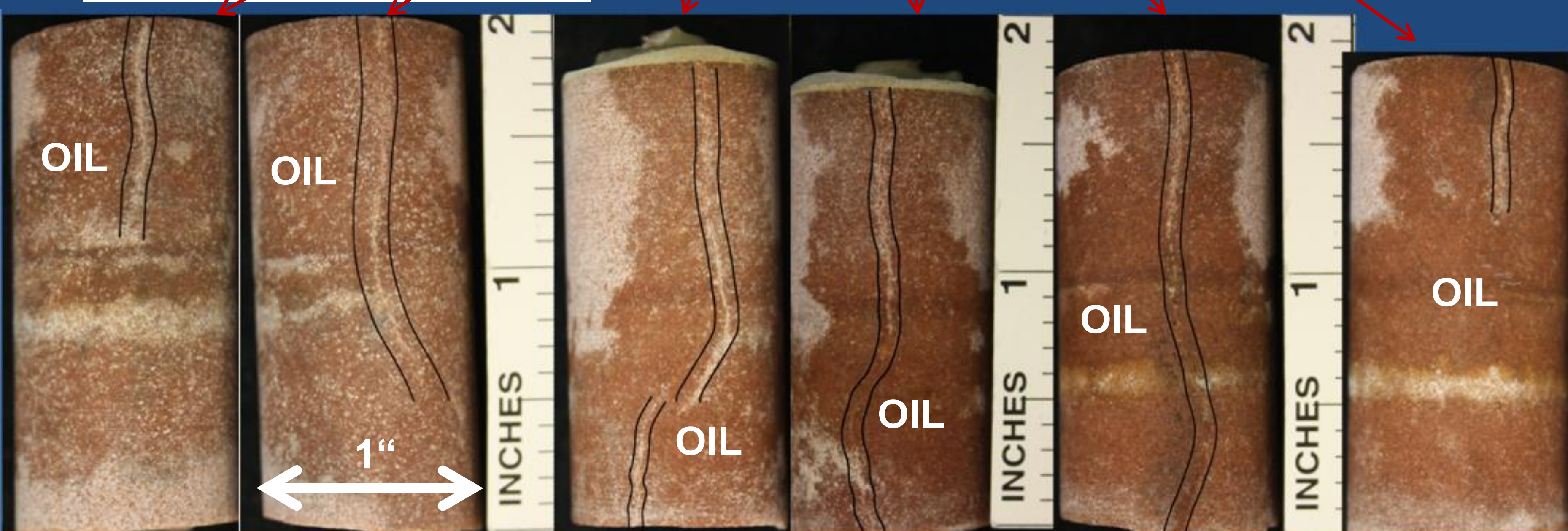
Lyons Sandstone- Spatial evolution of fractures





Fracture through going in the center, origin and tapers upward away from injection consistent with hypocenters in previous slide.

Fracture highlighted with black lines



Field scale mine-backs

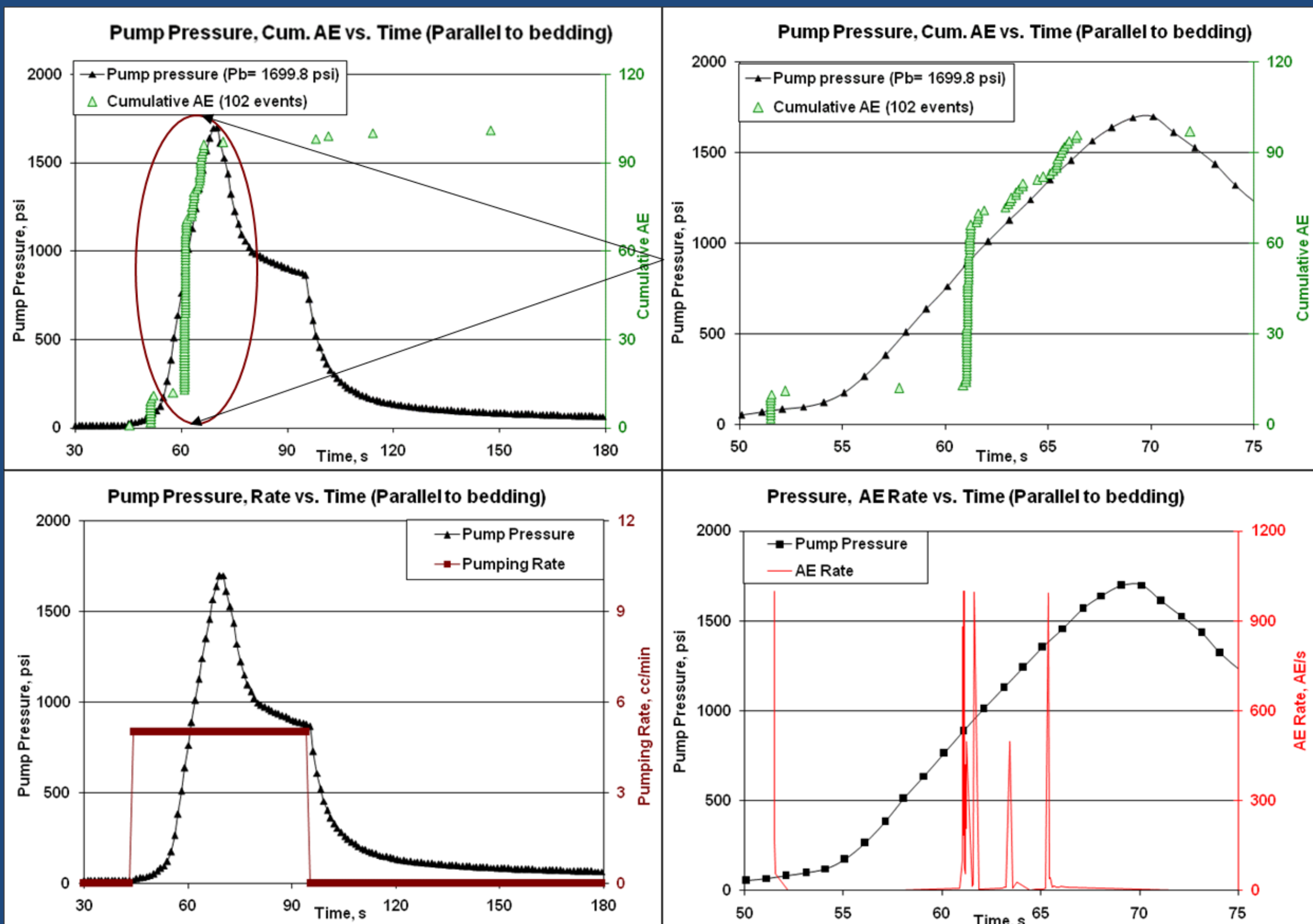
Warpinski et al., 1982

1 cm

Warpinski and Teufel, 1987

Syn-Shale: k=5 nd ; 4-samps

Stress applied parallel to bedding



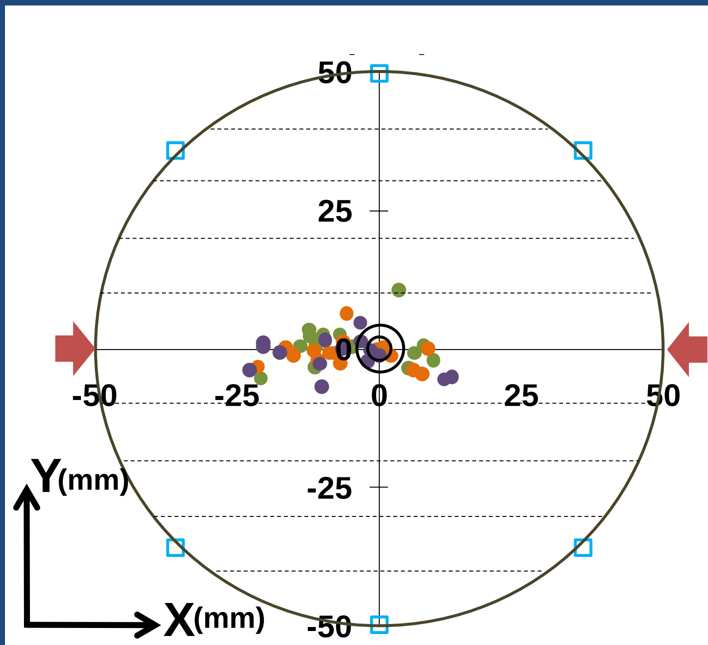
Pumping rate=5 cc/min

P_{bdwn}= 1700 psi

Total events= 102

- 42% of the recorded events were locatable
- Most of the AE distributed during initial stage

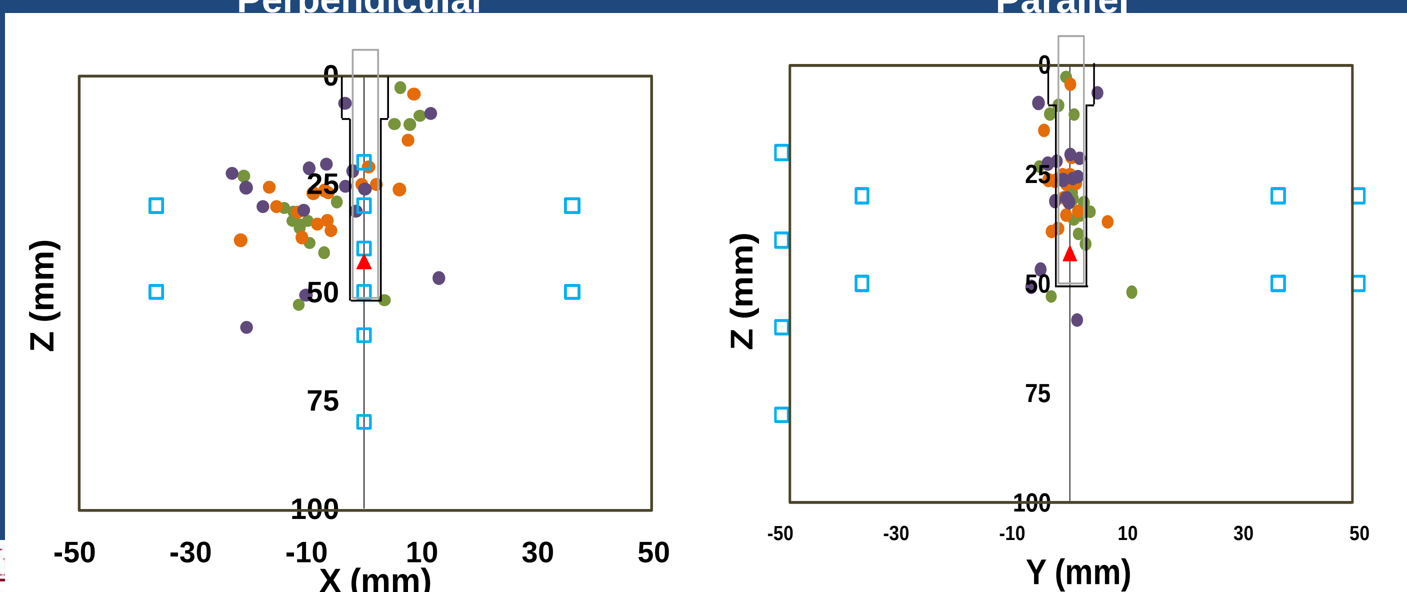
Syn-Shale- Stress applied parallel to bedding



- Fracture subparallel to stress applied
- 47 events were located
- 42% of events recorded were locatable
- Limited development of fracture plane
- Fairly narrowly confined to a plane

Perpendicular

Parallel

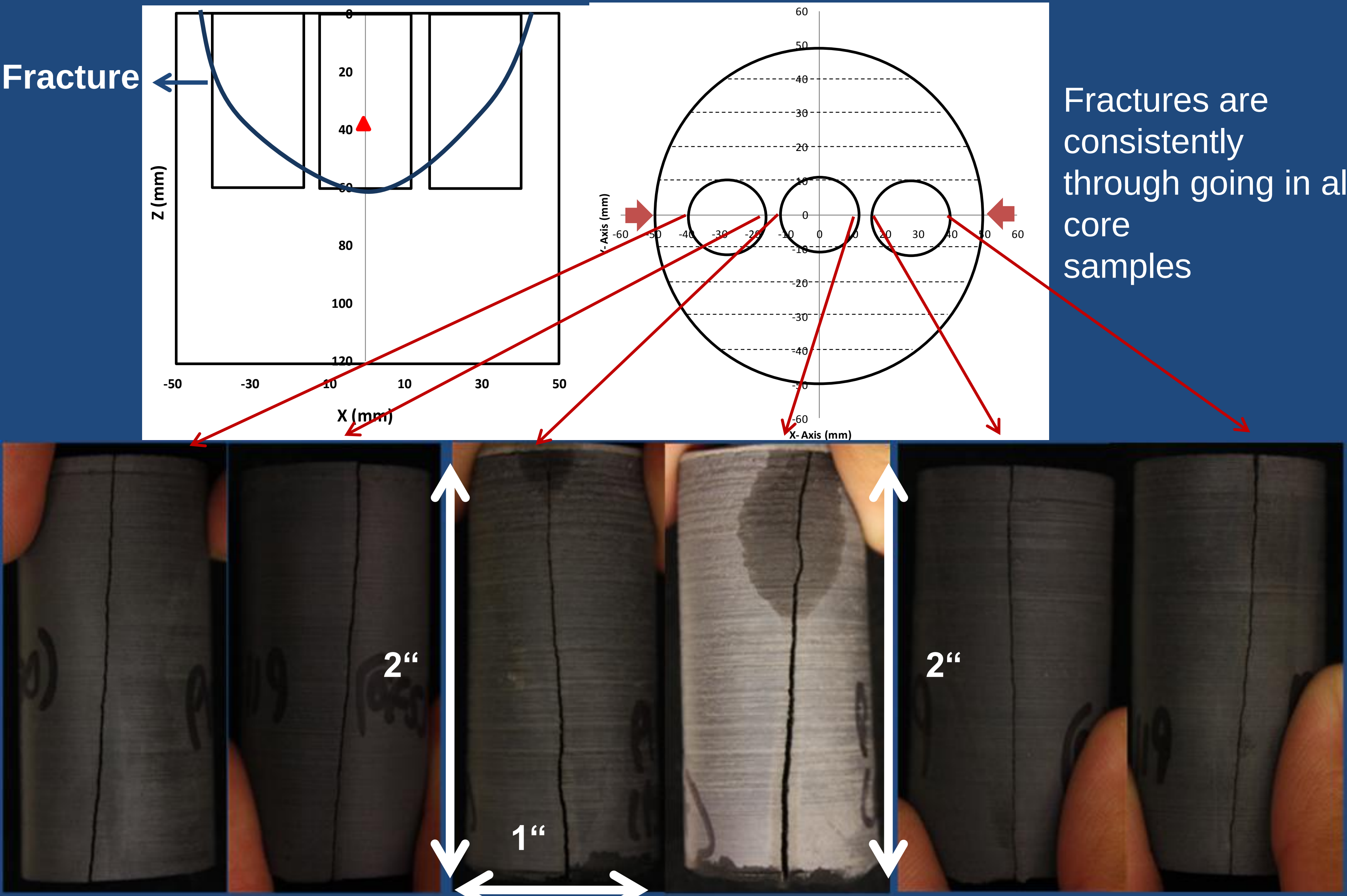


Time

Early
Intermediate
Late

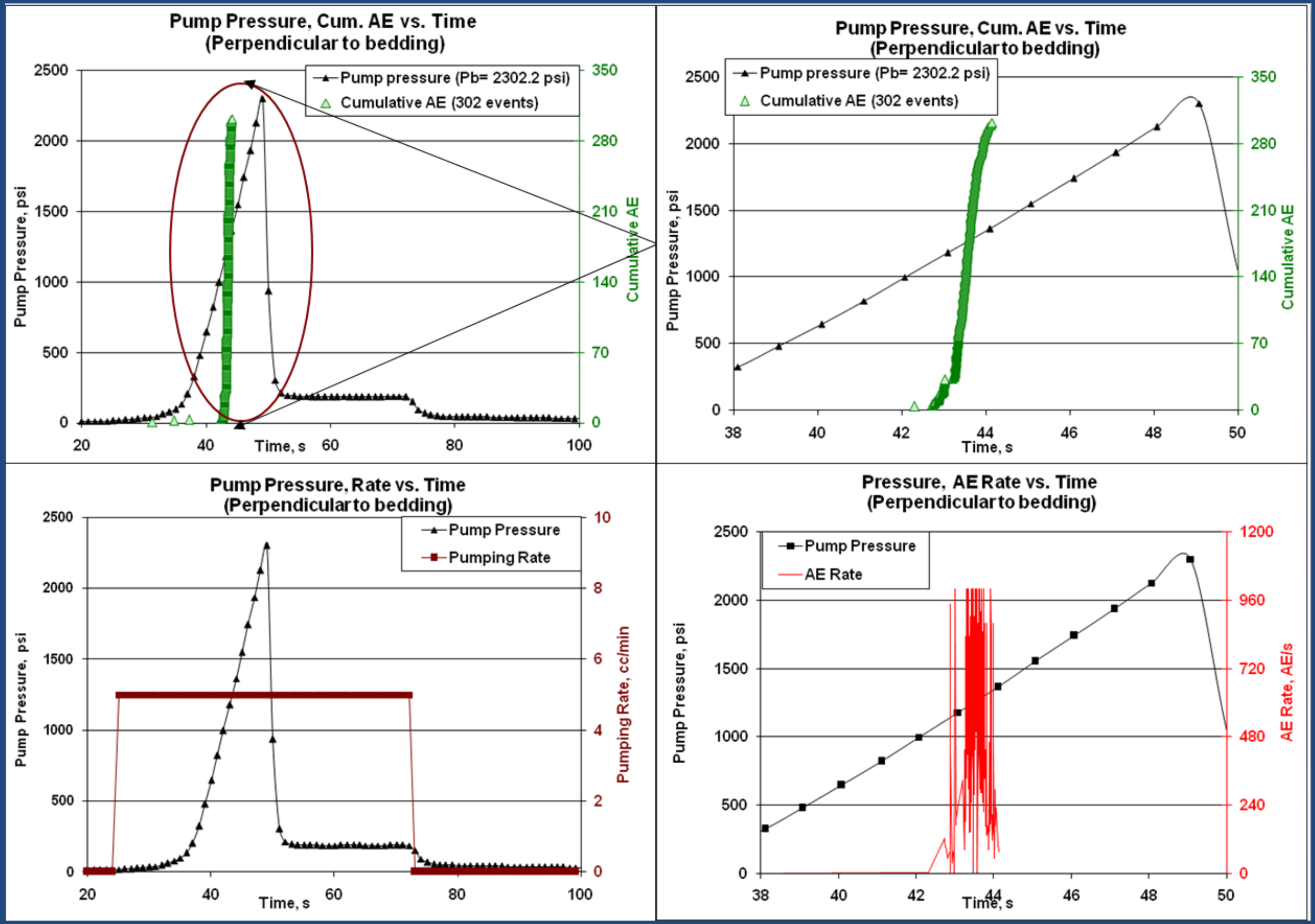
▲ **Perforation**
Sensor

Syn-Shale- Stress applied parallel to bedding



Fractures are consistently through going in all core samples

Syn-Shale- Stress applied perpendicular to bedding



4-samps

Pumping rate=5 cc/min

P_{bdwn} =2300 psi

Total events= 302

- Majority of events before breakdown
- 22% of the recorded events were locatable

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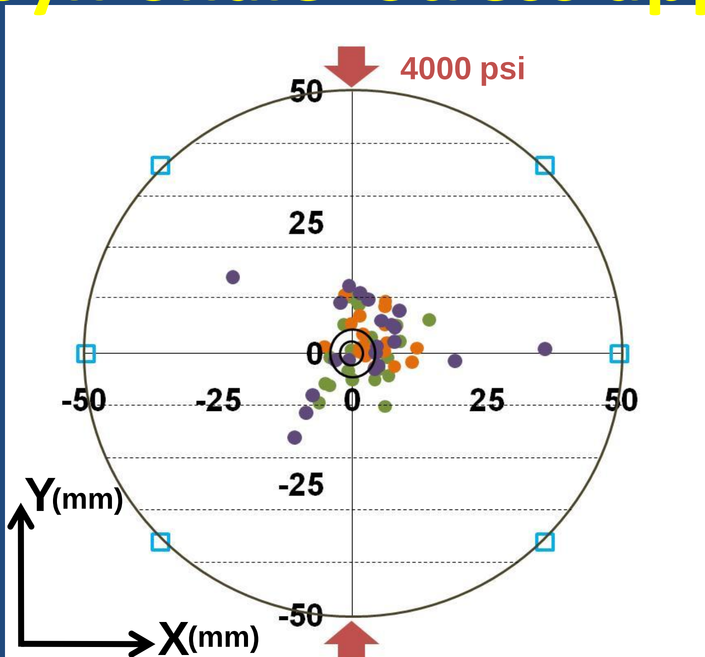
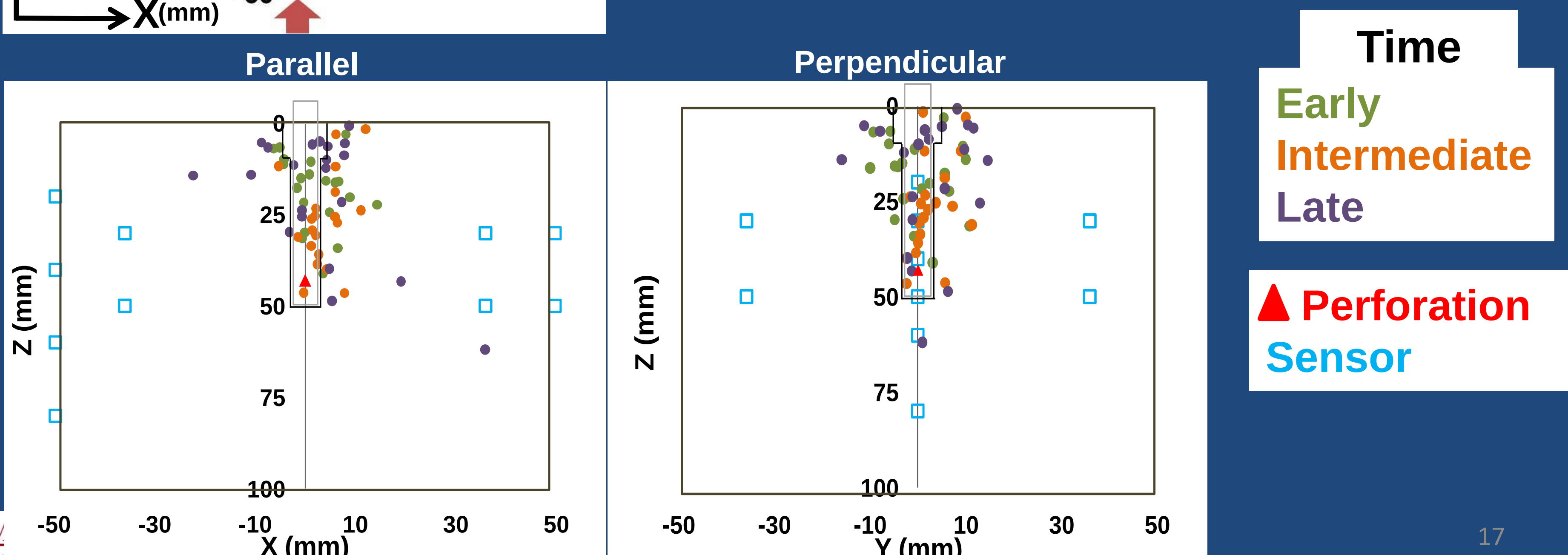
Syn-Shale- Stress applied perpendicular to bedding

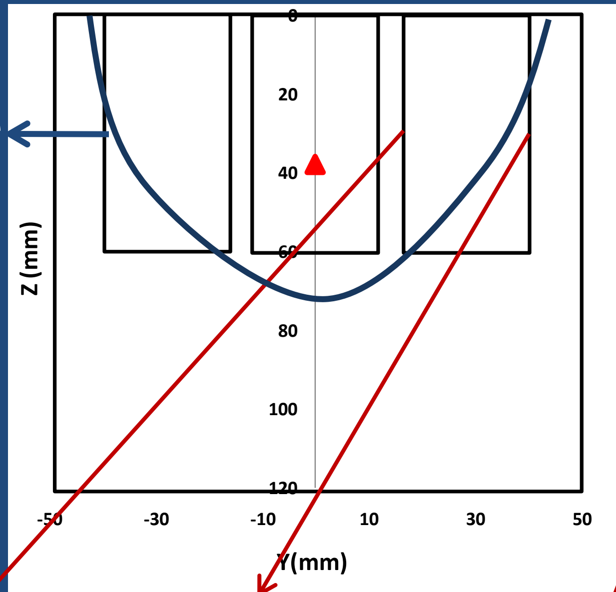


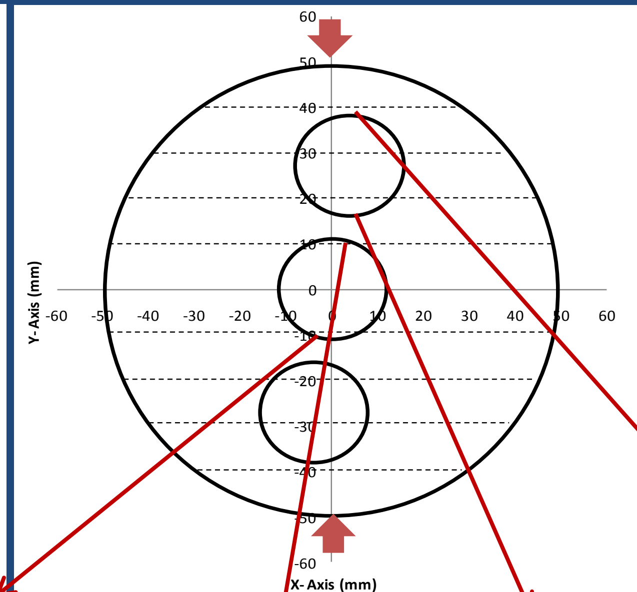
- A local cluster developed around the borehole
- Deviation of the fracture direction from maximum stress orientation is 25 , consistent with calculations
- 66 events were located



Syn-Shale- Stress applied perpendicular to bedding

Fracture





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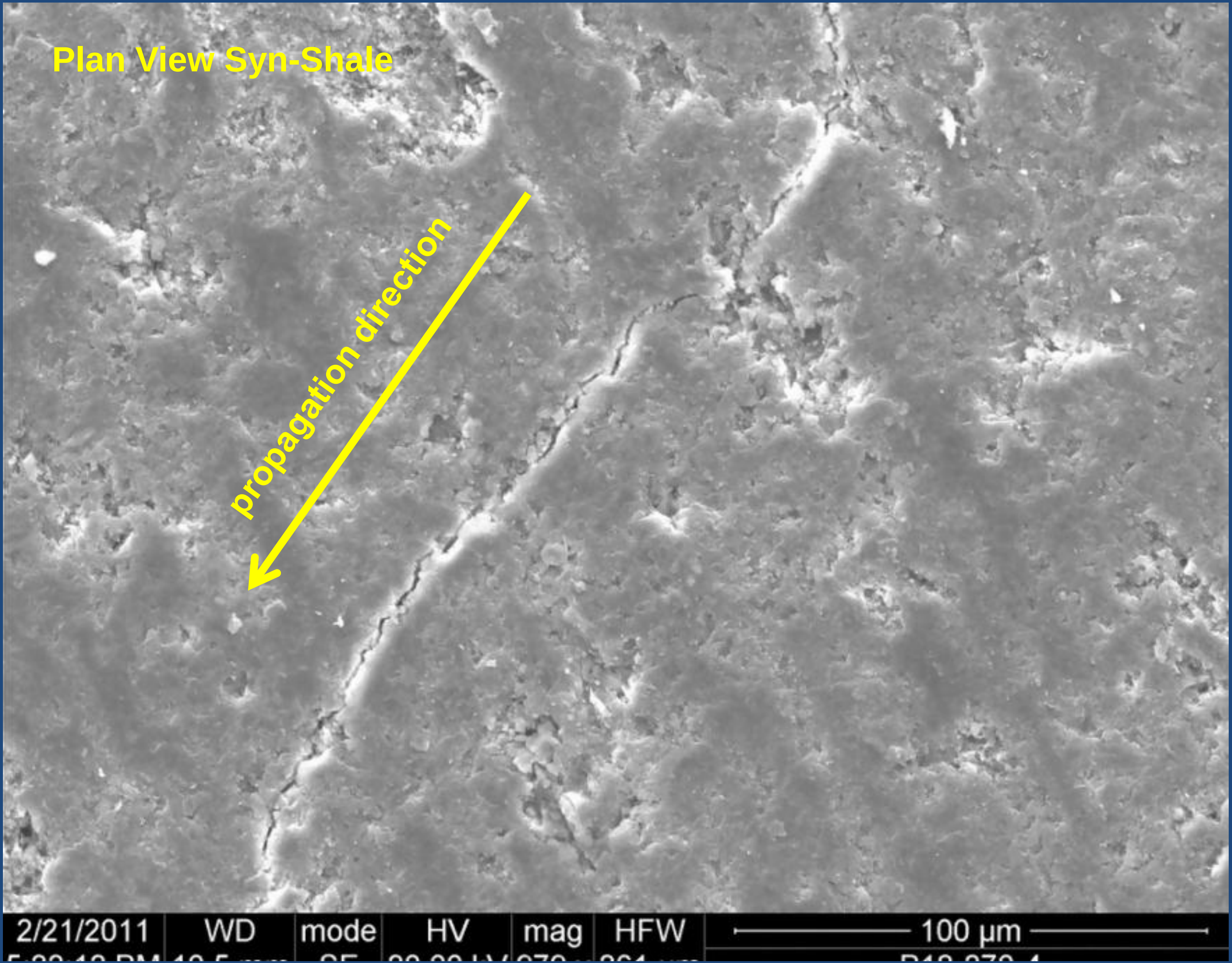
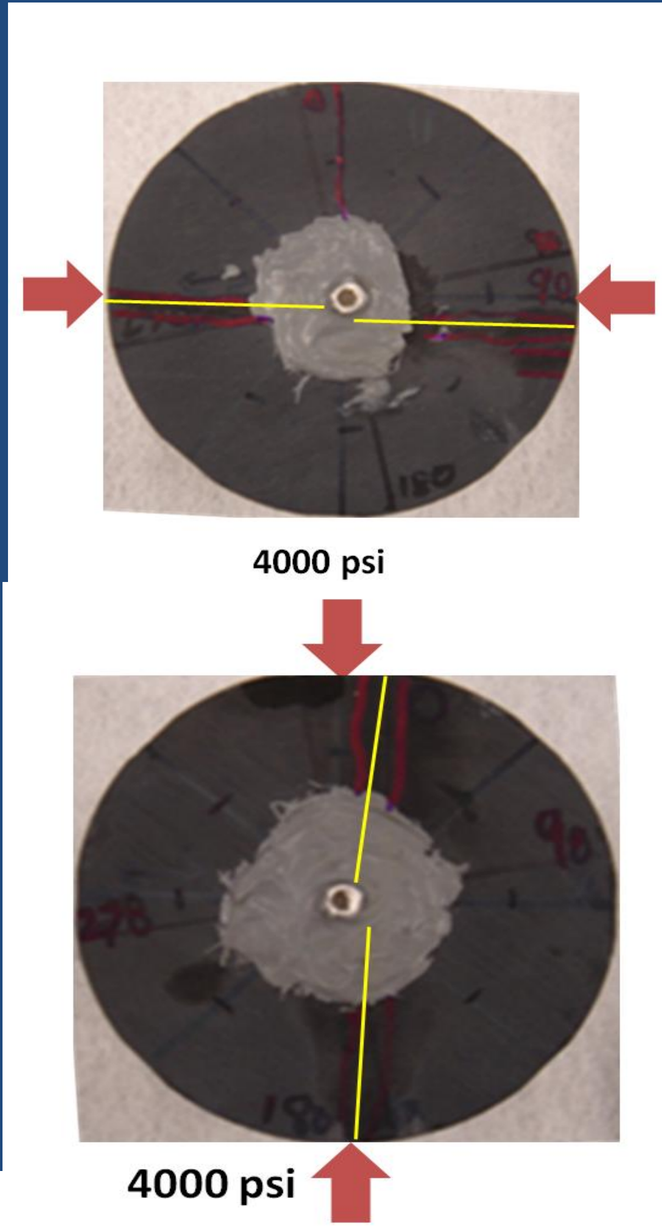
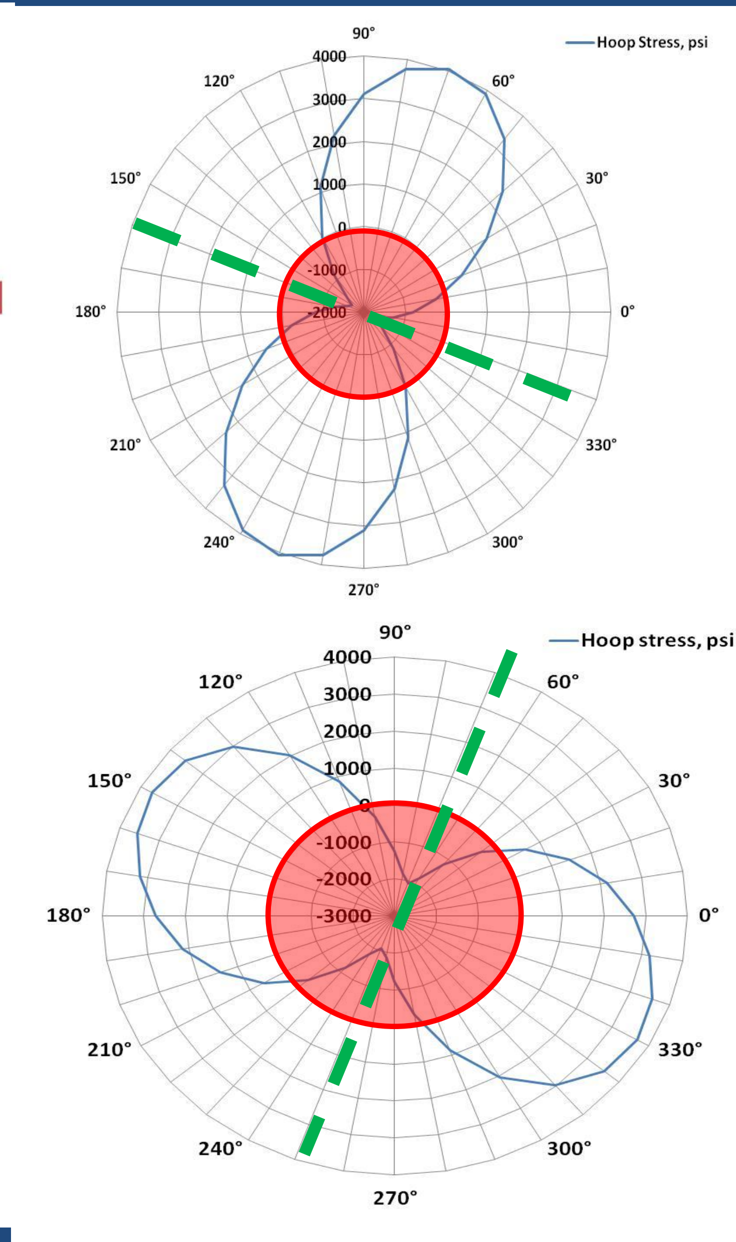

Plan View Syn-Shale
propagation direction
2/21/2011
WD
mode
HV
mag
HFW
100 µm

Stress distribution-Anisotropic reservoirs

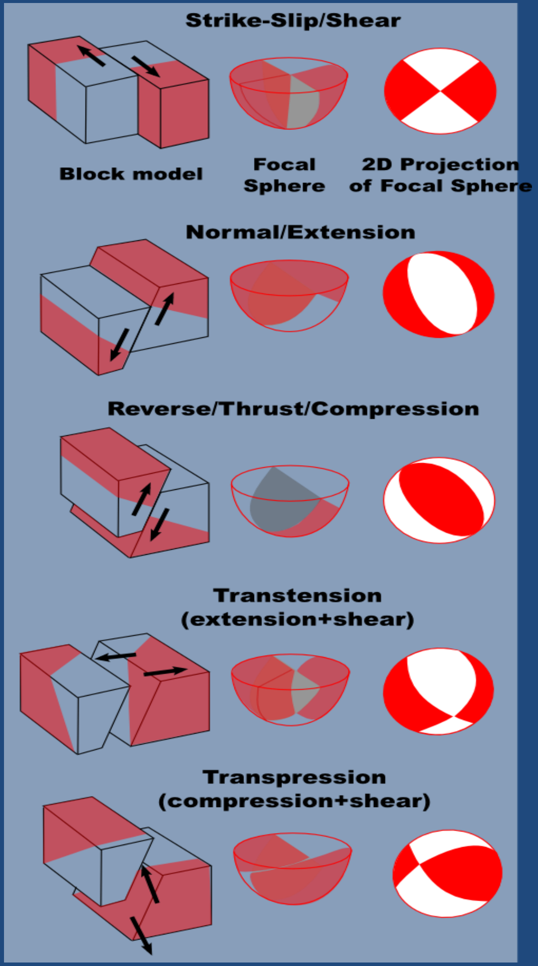




- Hoop stress symmetry different from isotropic materials
- Deviation depends on anisotropy and far field stress
- Fracture direction deviates from the maximum stress direction by 20

Aadnoy, 1987

Focal Mechanism Studies



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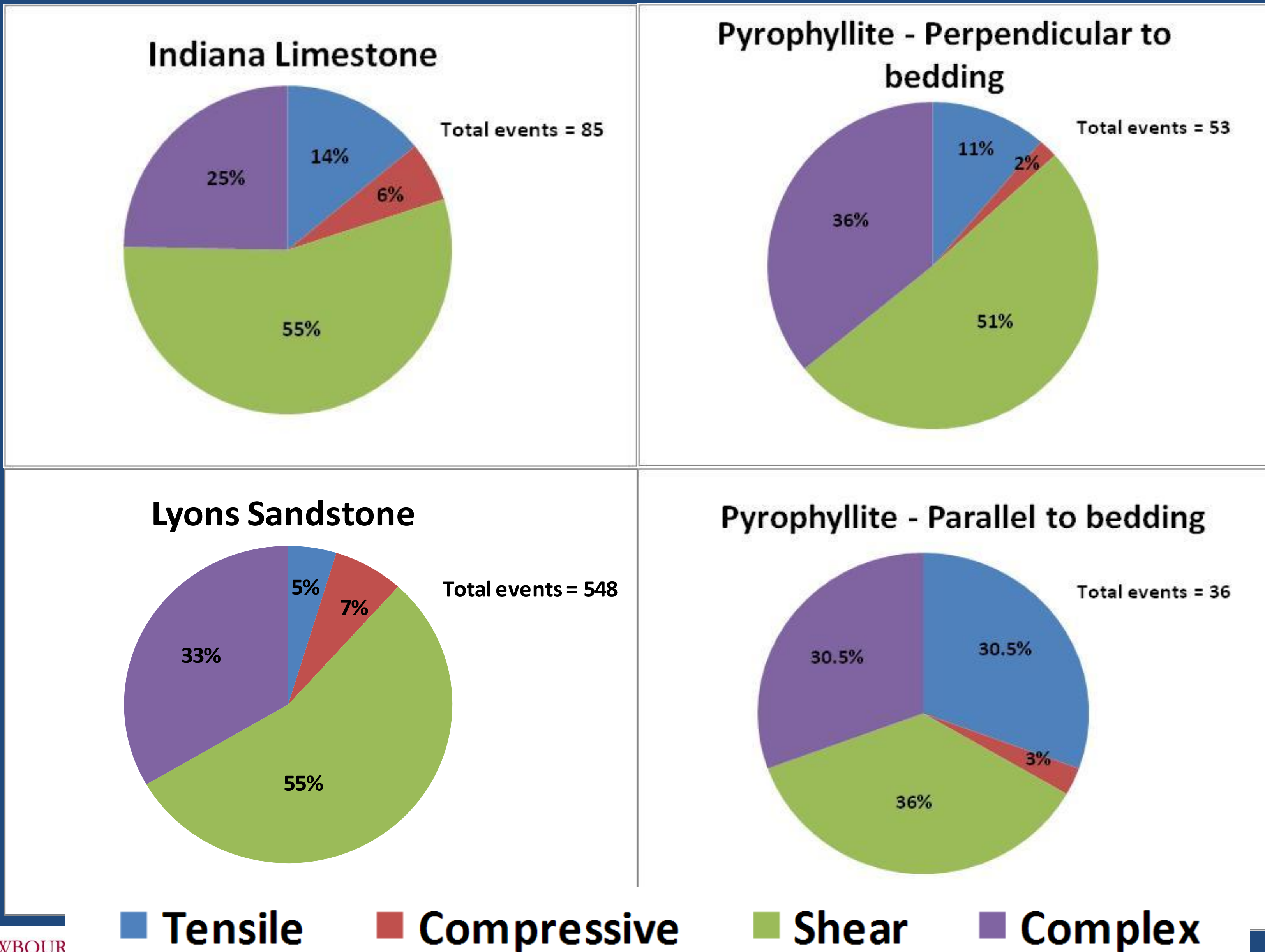
FOCAL MECHANISMS



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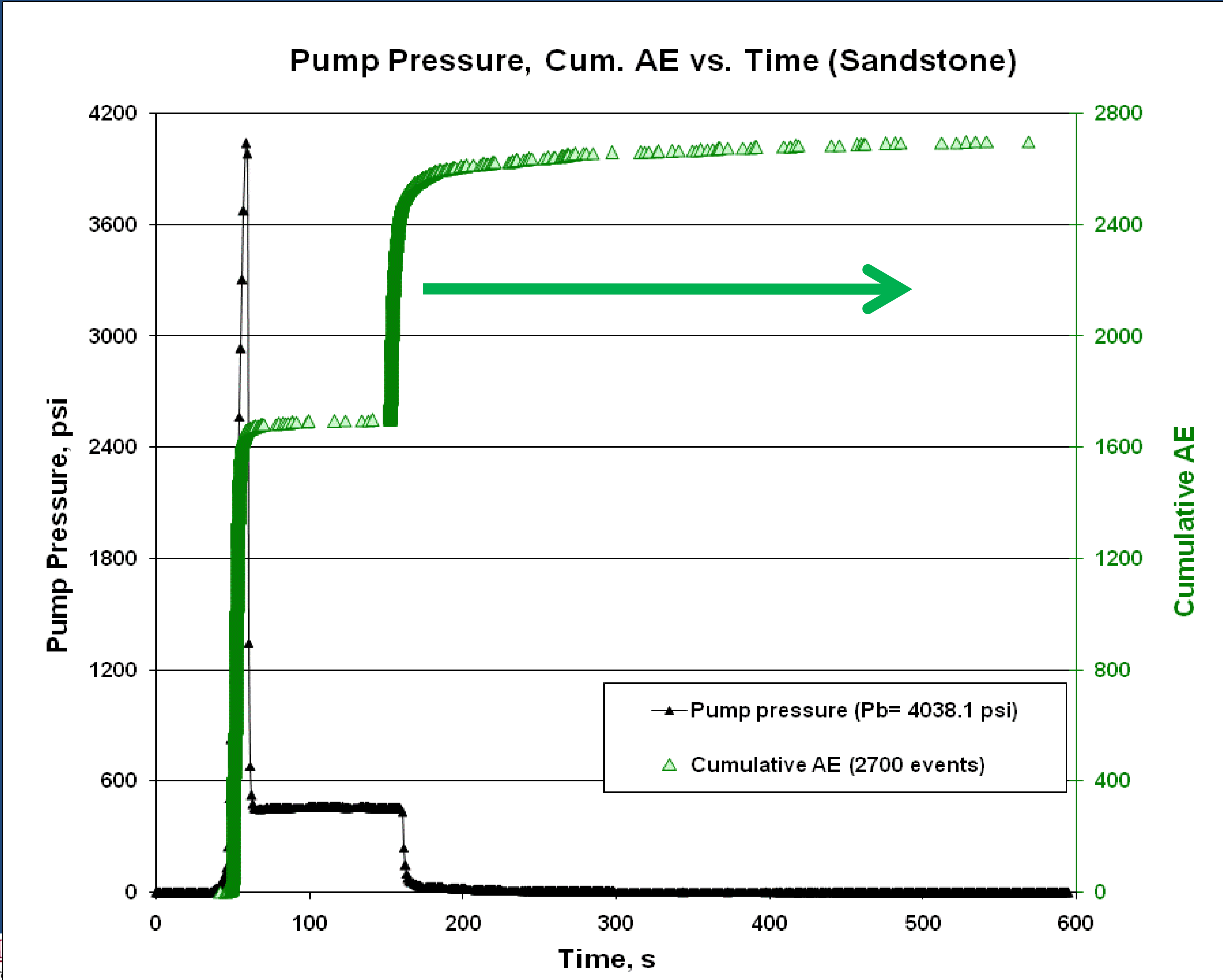
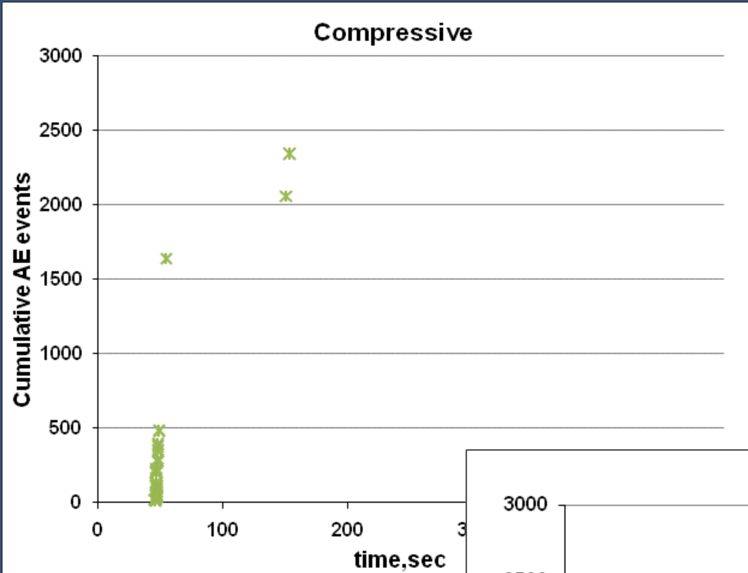
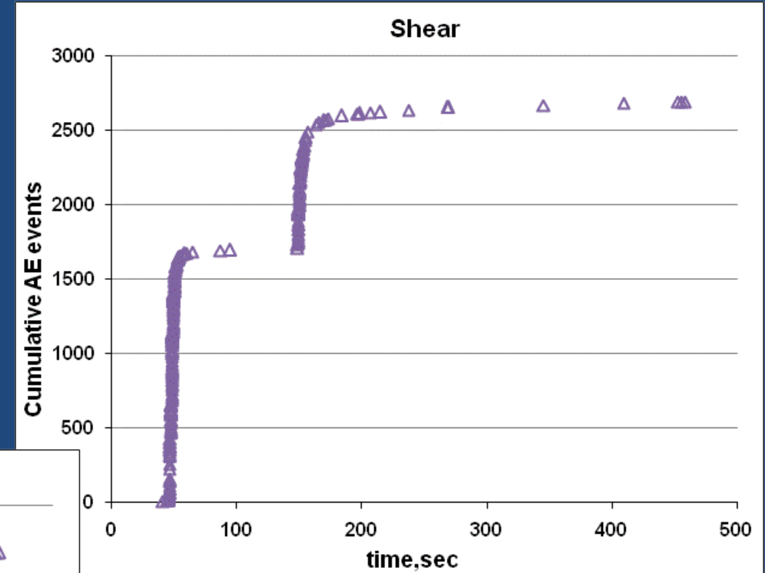
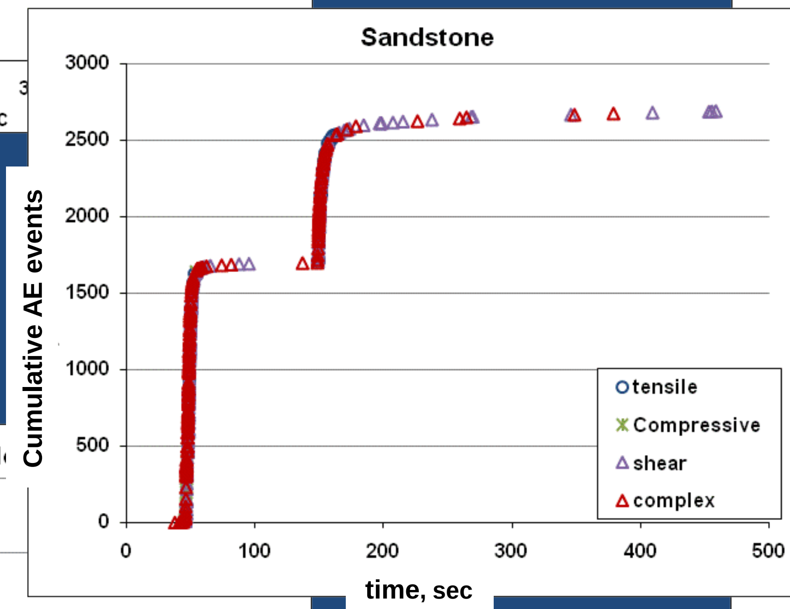
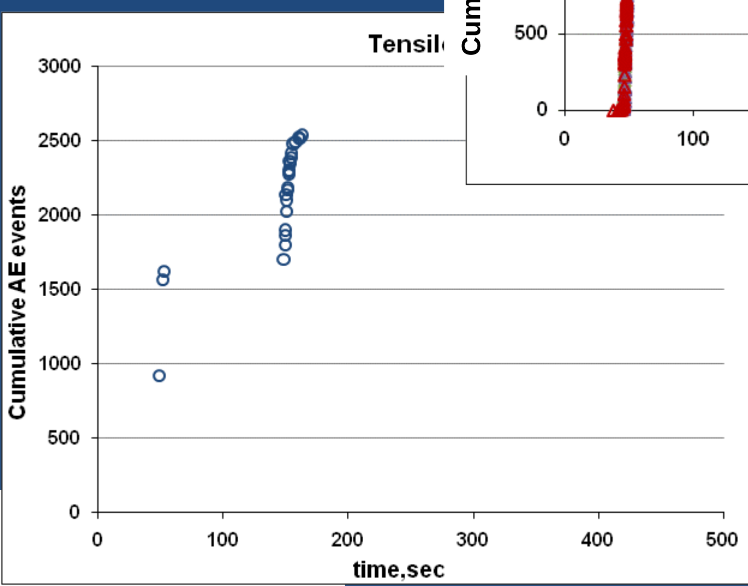

Pump Pressure, Cum. AE vs. Time (Sandstone)
Pump Pressure, psi
0
600
1200
1800
2400
3000
3600
4200
Cumulative AE
0
400
800
1200
1600
2000
2400
2800
Time, s
0
100
200
300
400
500
600
Pump pressure (Pb= 4038.1 psi)
Cumulative AE (2700 events)

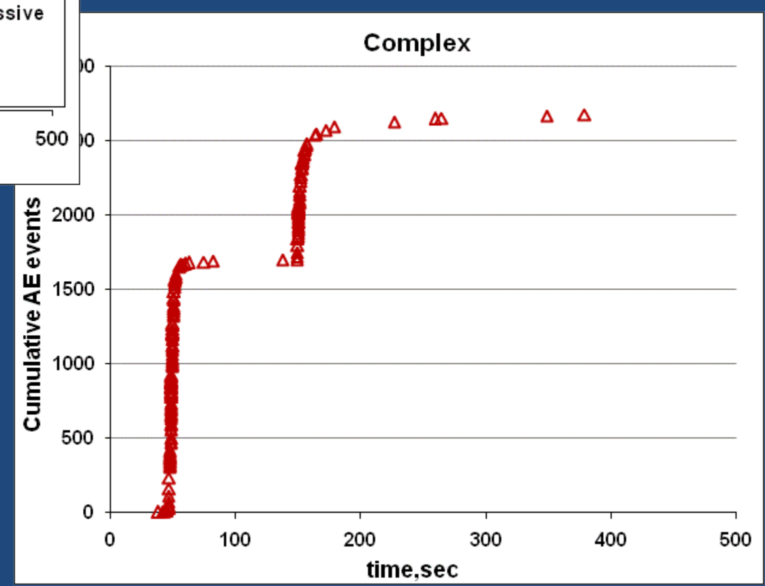
Sandstone


Compressive
Cumulative AE events
3000
2500
2000
1500
1000
500
0
0
100
200
time,sec


Shear
Cumulative AE events
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
500
time,sec


Sandstone
Cumulative AE events
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
500
time, sec
tensile
Compressive
shear
complex


Cumulative AE events
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
500
time,sec


Complex
Cumulative AE events
2000
1500
1000
500
0
0
100
200
300
400
500
time,sec

SEM Observations of Hydraulic Fractures

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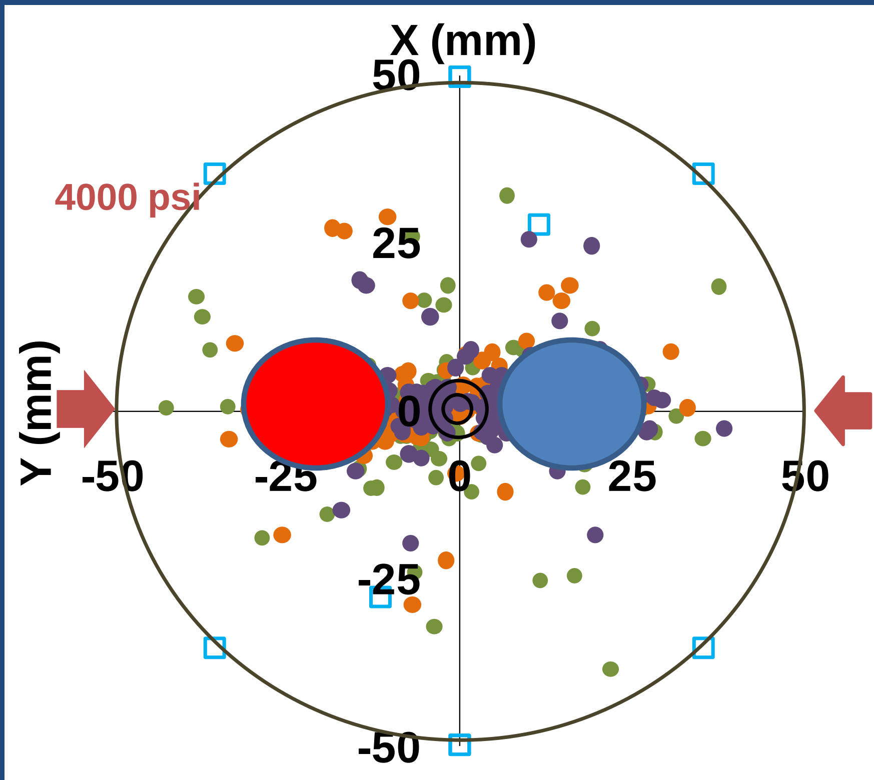
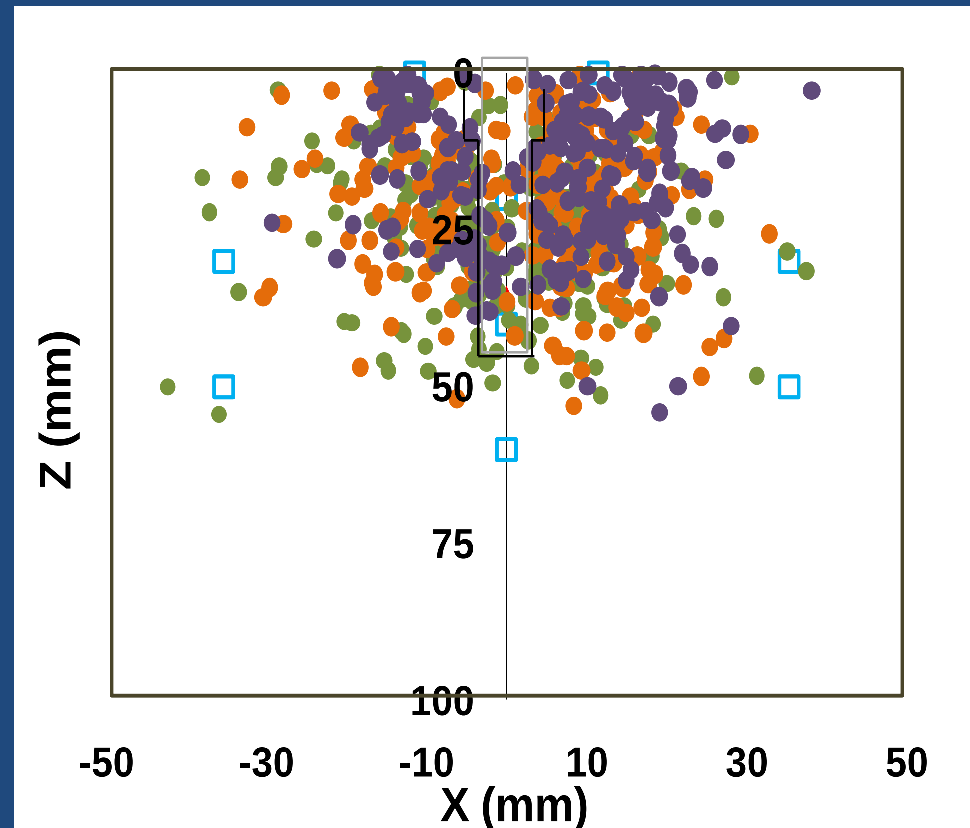
Lyons Sandstone



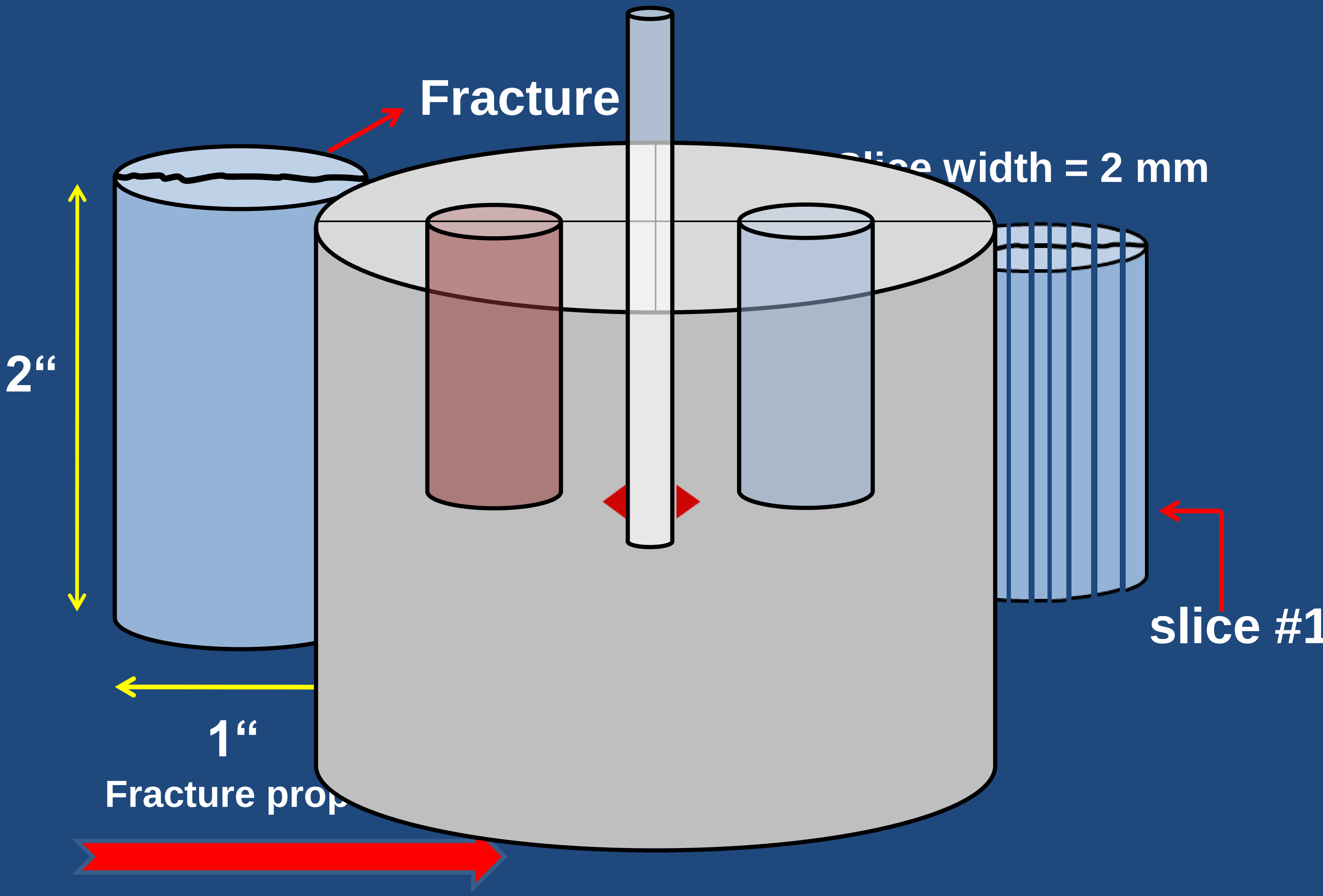
Perpendicular



Time

Early
Intermediate
Late

▲ Perforation
Sensor



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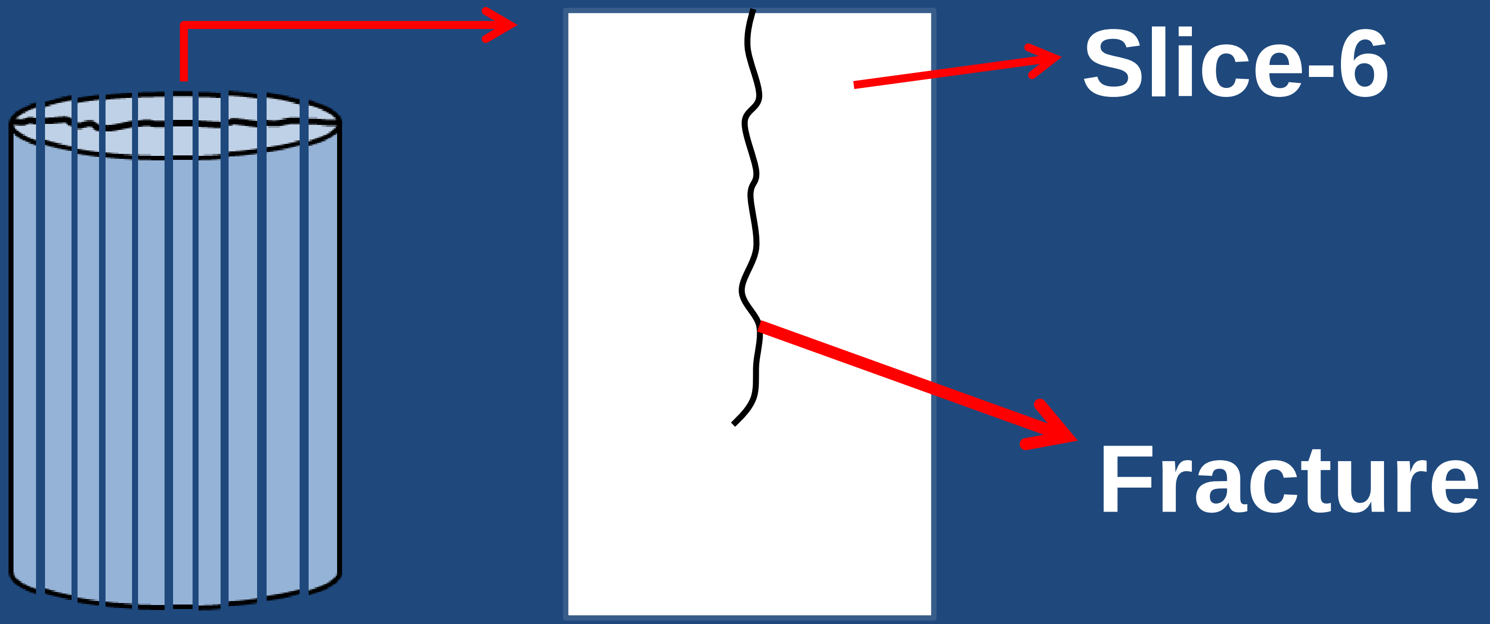
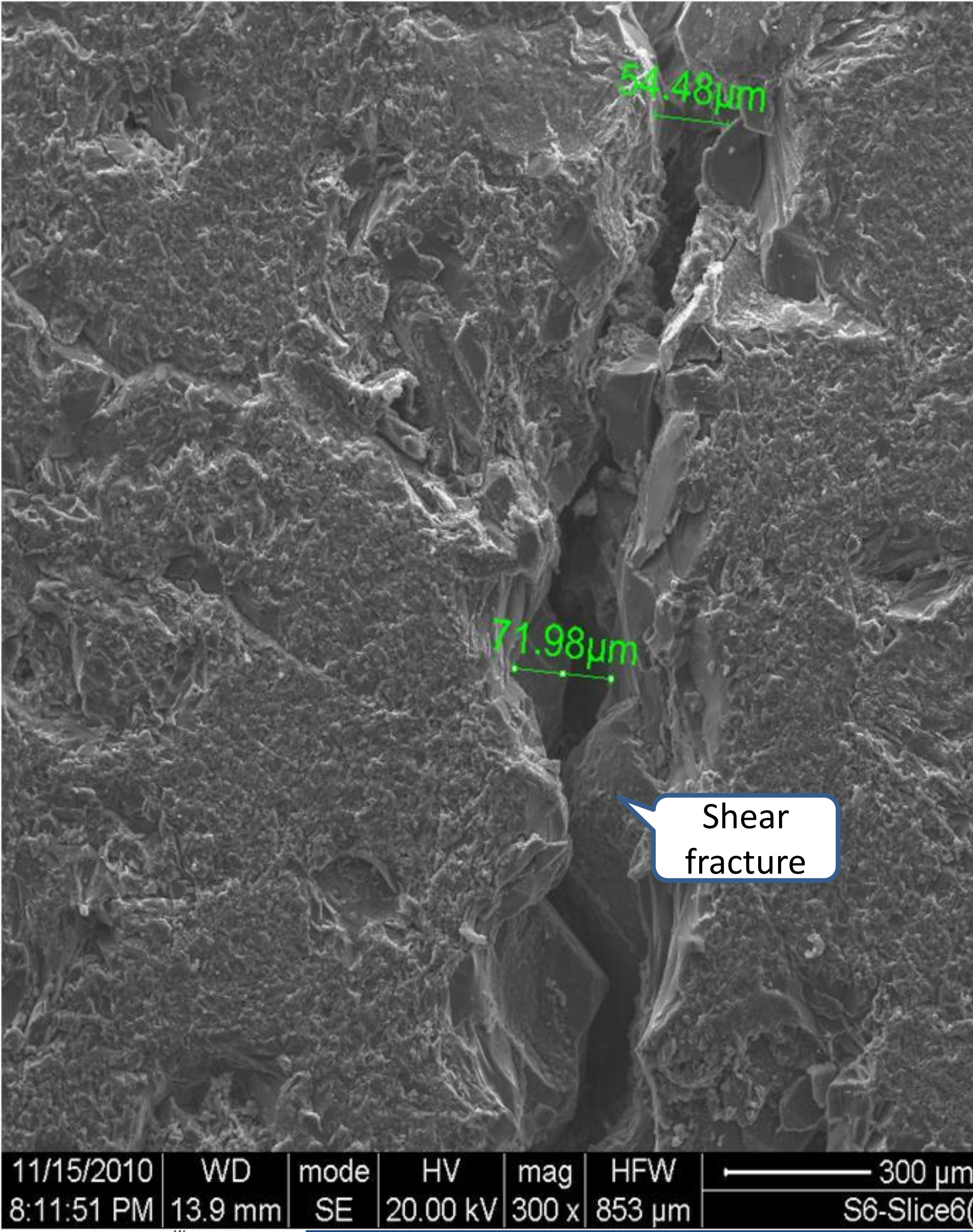
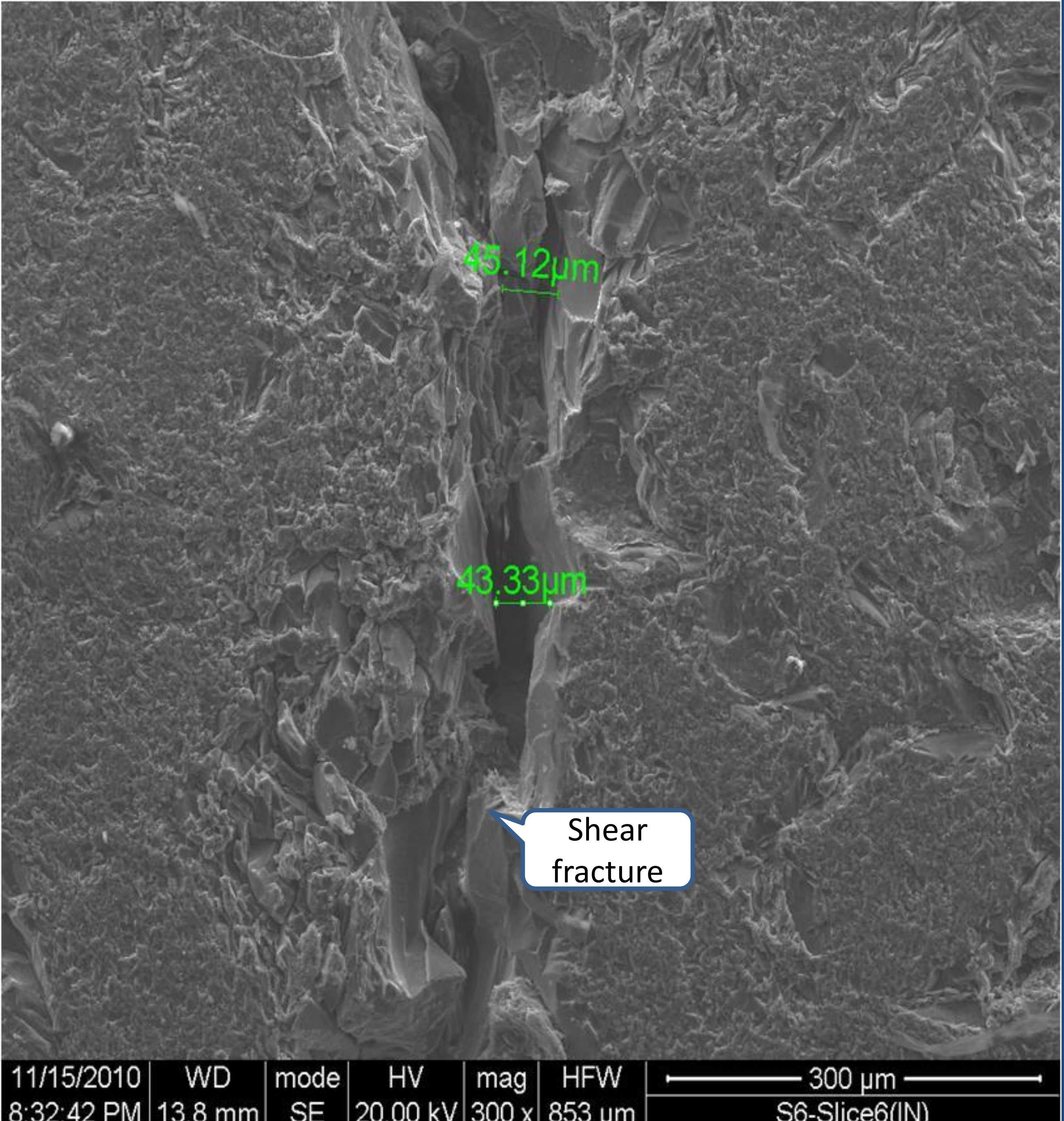
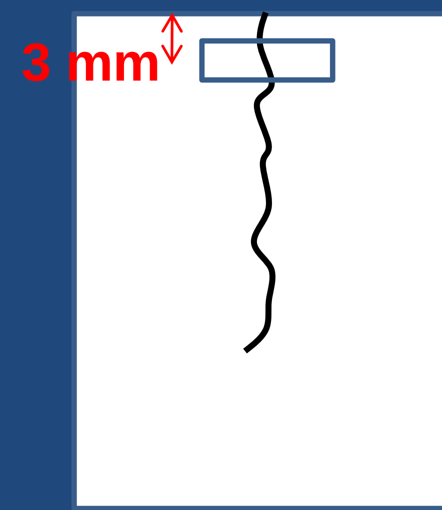
SEM along Fracture front propagation is toward viewer




54.48µm
71.98µm
Shear
fracture
11/15/2010
8:11:51 PM
WD
13.9 mm
mode
SE
HV
20.00 kV
mag
300 x
HFW
853 µm
300 µm
S6-Slice6(

SEM:





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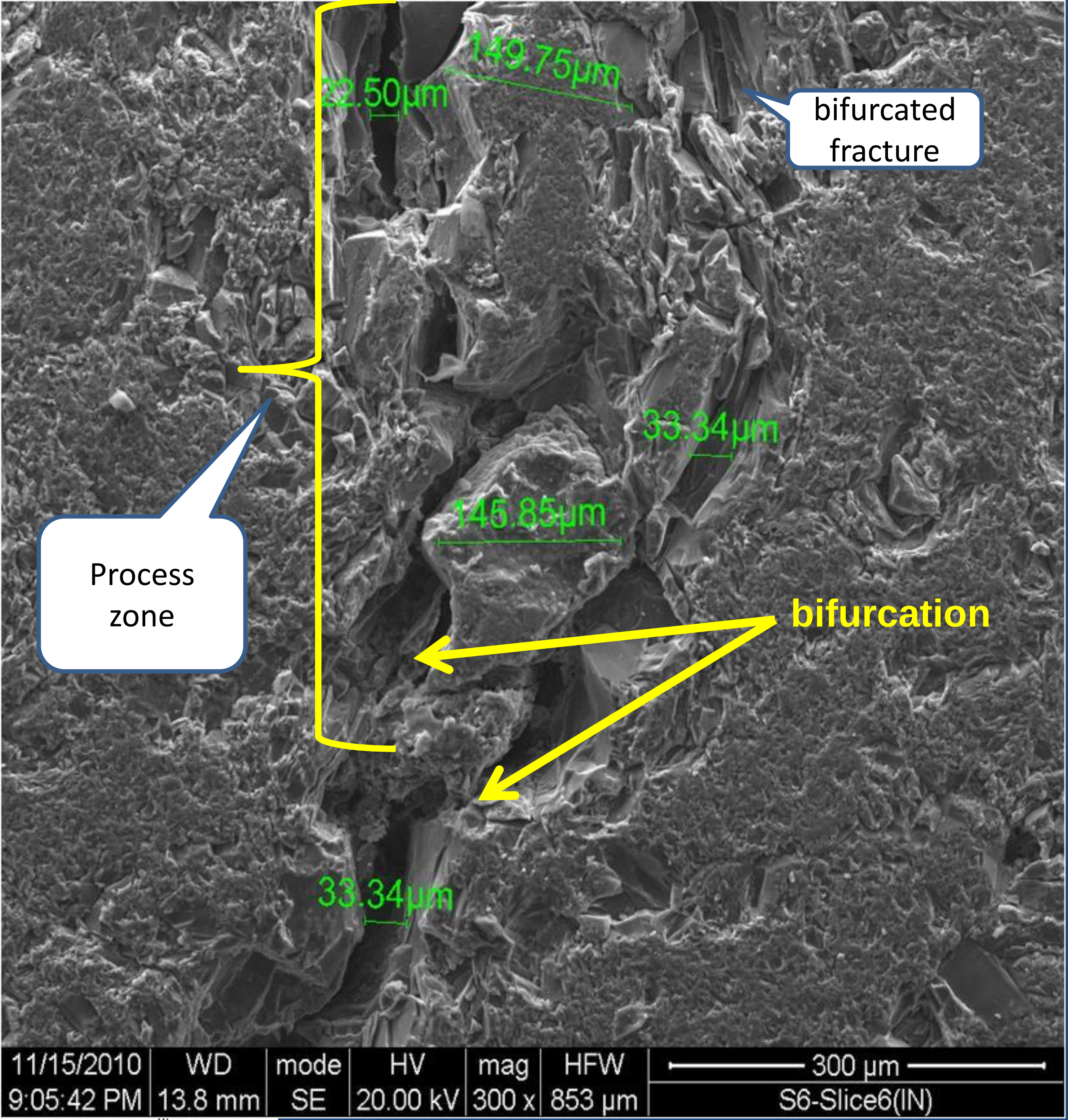
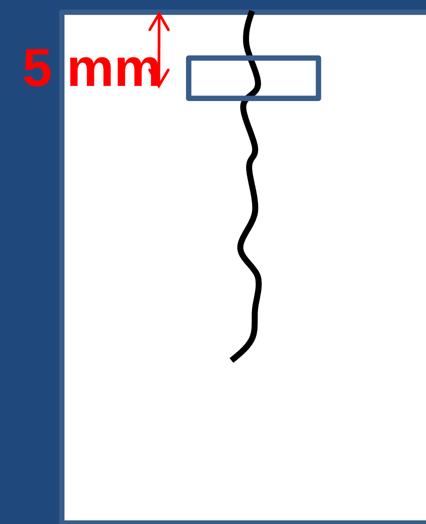
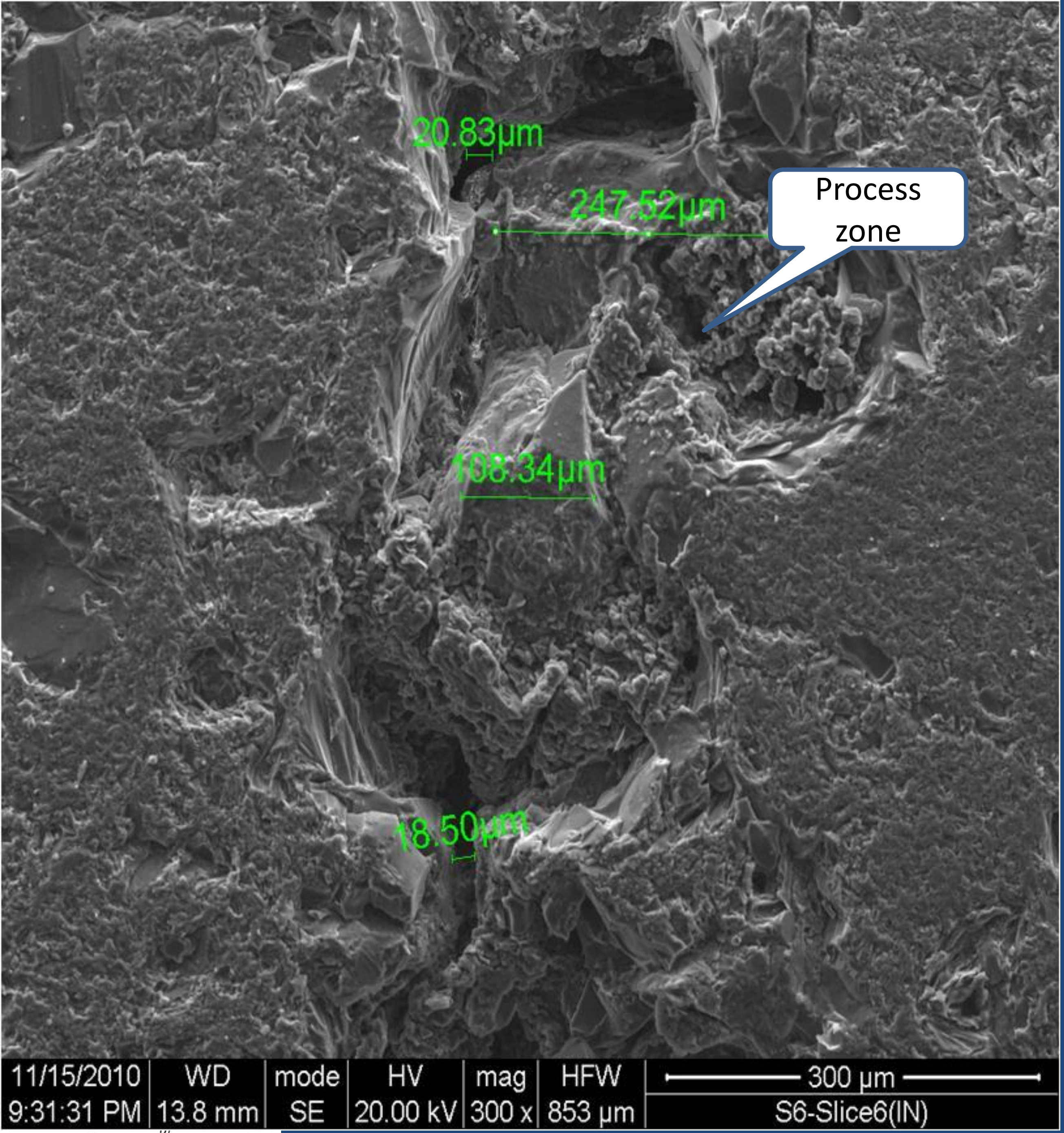
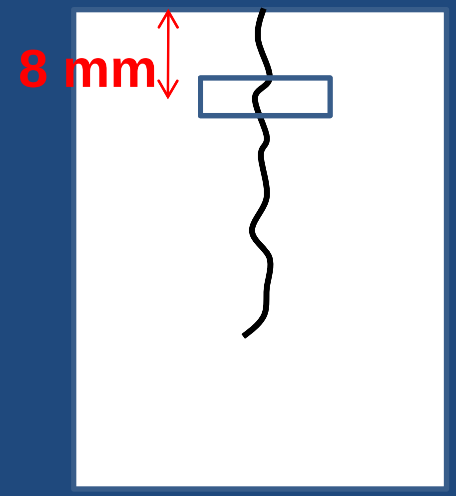
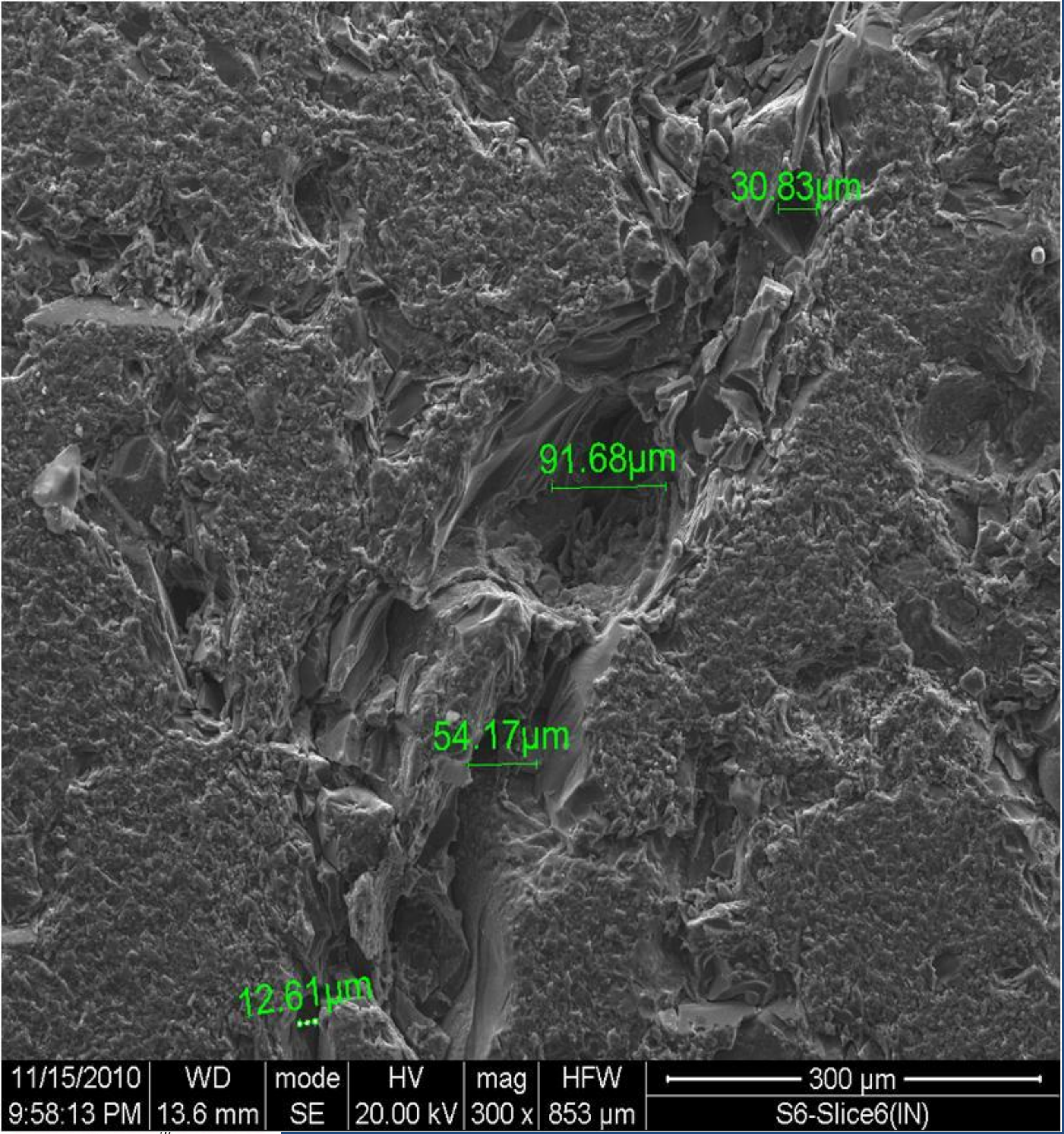
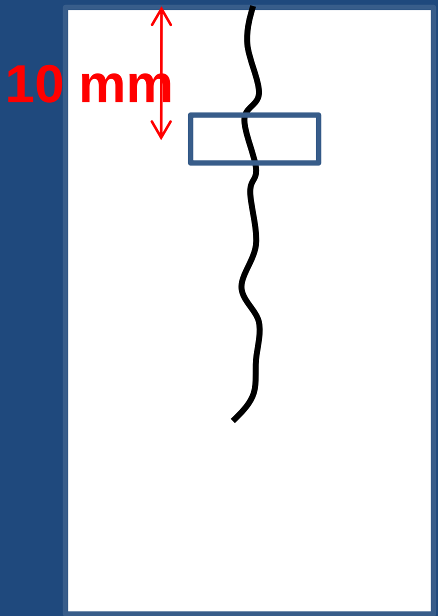

149.75μm
22.50μm
bifurcated fracture
33.34μm
145.85μm
Process zone
bifurcation
33.34μm
11/15/2010 9:05:42 PM
WD 13.8 mm
mode SE
HV 20.00 kV
mag 300 x
HFW 853 μm
300 μm
S6-Slice6(IN)

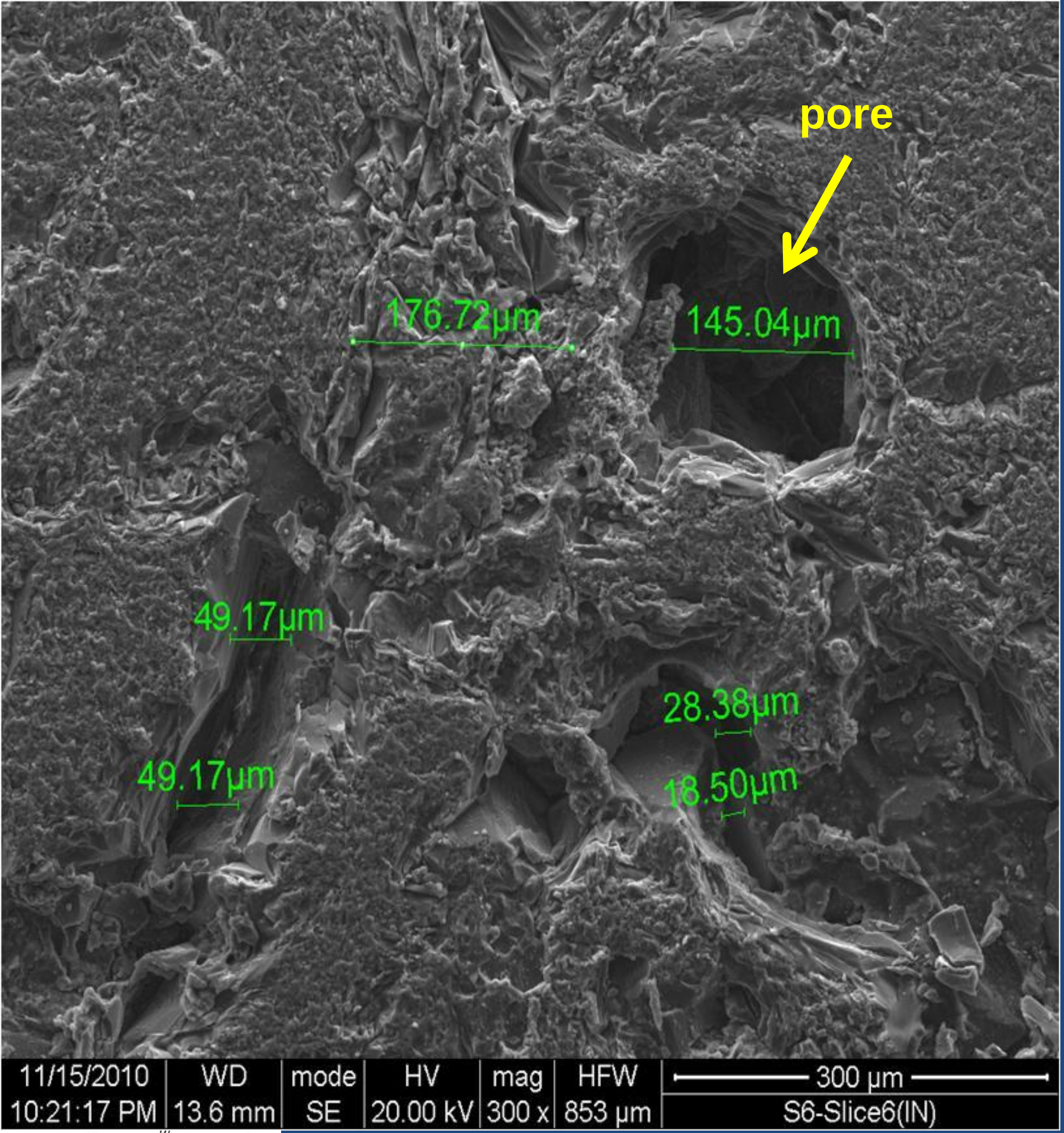

5 mm

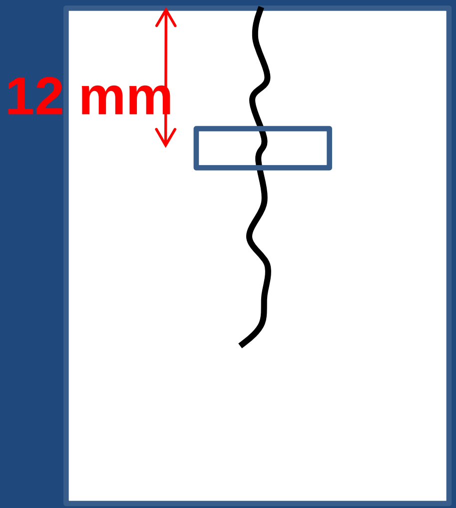

20.83µm
247.52µm
Process zone
108.34µm
18.50µm
11/15/2010 9:31:31 PM
WD 13.8 mm
mode SE
HV 20.00 kV
mag 300 x
HFW 853 µm
300 µm
S6-Slice6(IN)

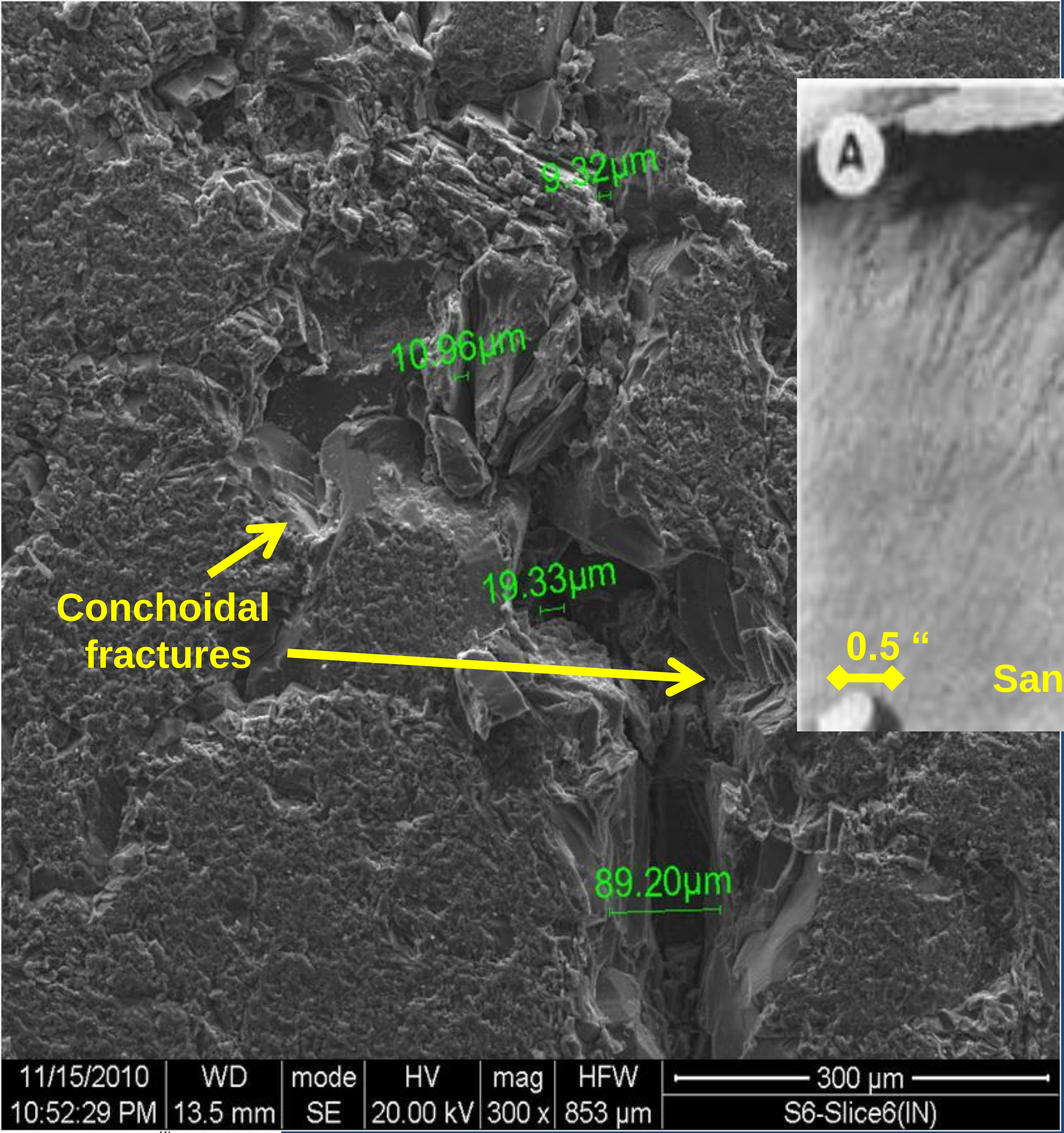

8 mm

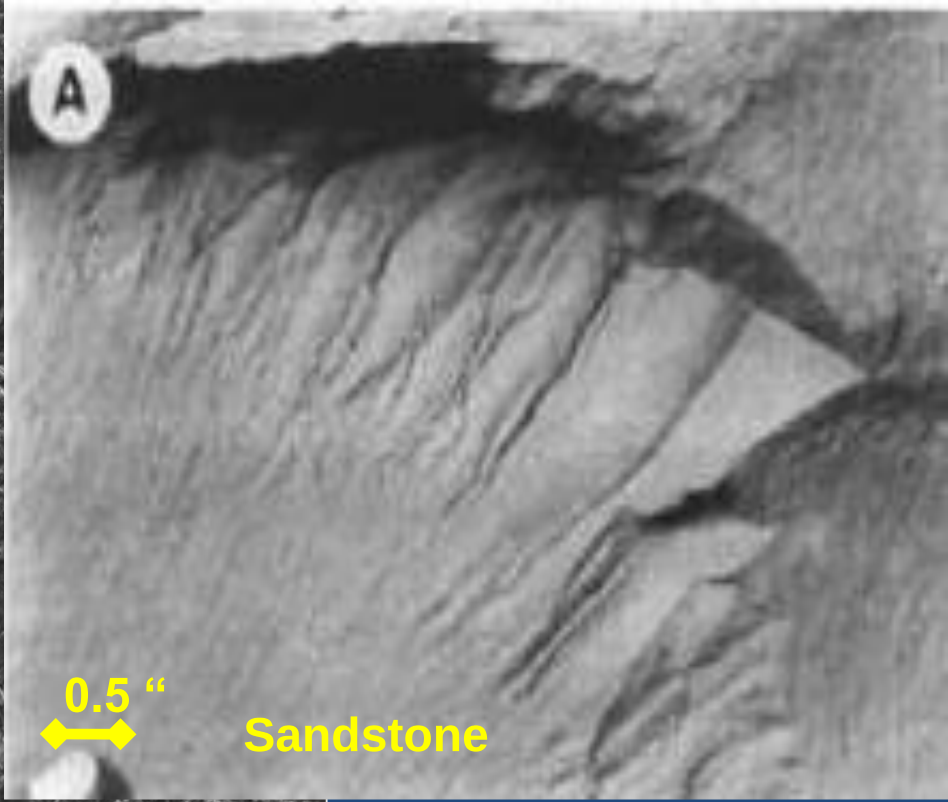

30.83µm
91.68µm
54.17µm
12.61µm
11/15/2010
9:58:13 PM
WD
13.6 mm
mode
SE
HV
20.00 kV
mag
300 x
HFW
853 µm
300 µm
S6-Slice6(IN)

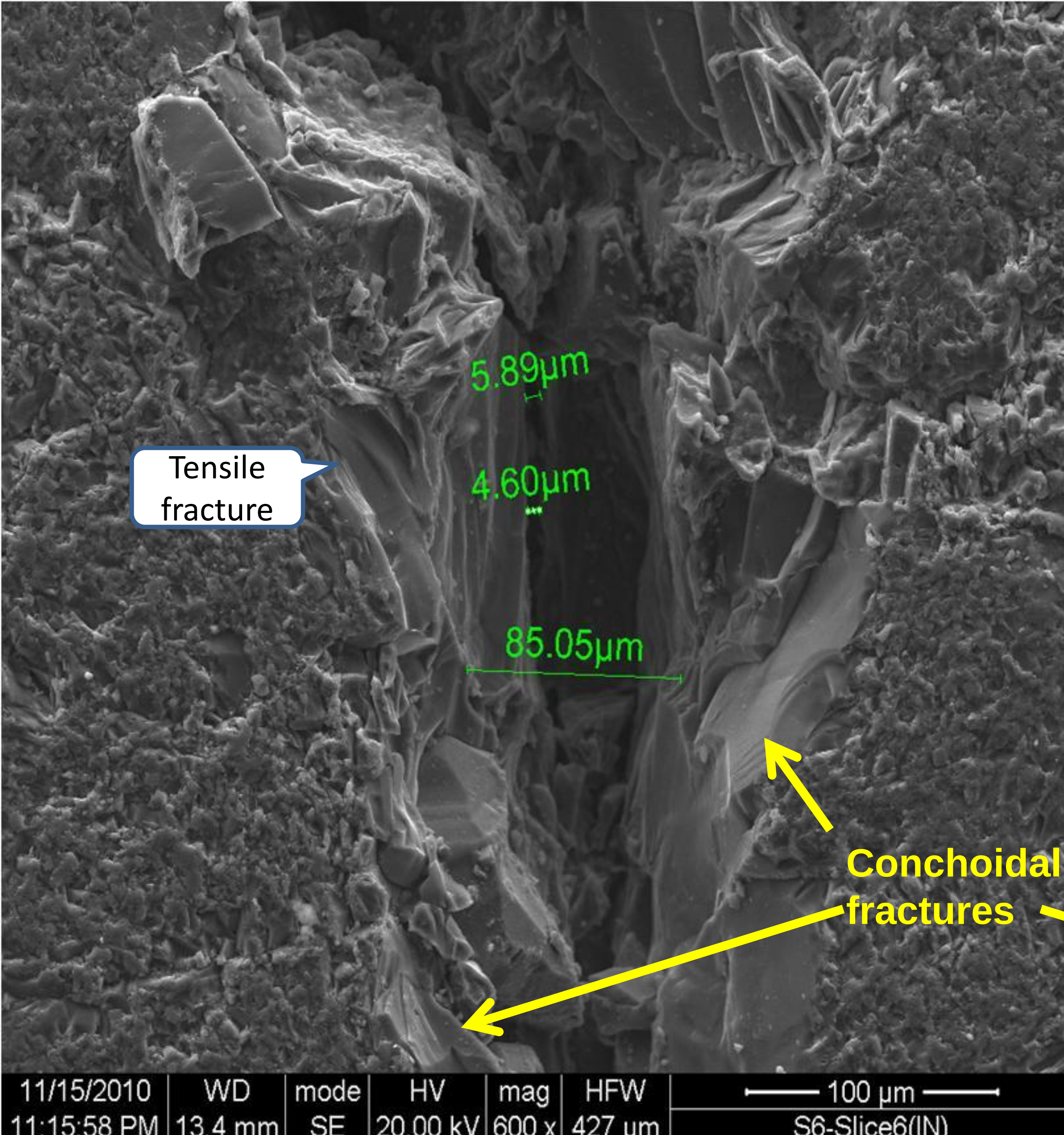

10 mm

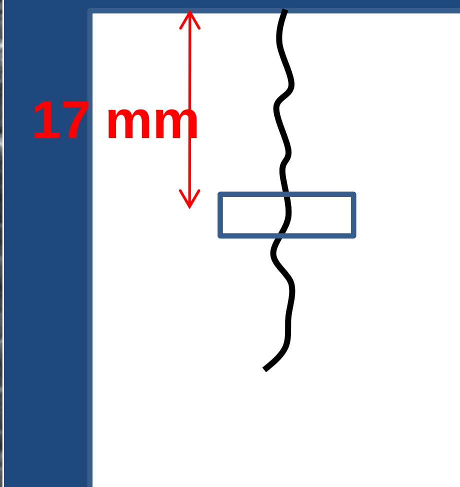

pore
176.72μm
145.04μm
49.17μm
49.17μm
28.38μm
18.50μm
11/15/2010
10:21:17 PM
WD
13.6 mm
mode
SE
HV
20.00 kV
mag
300 x
HFW
853 μm
300 μm
S6-Slice6(IN)


12 mm


9.32µm
10.96µm
19.33µm
89.20µm
Conchoidal
fractures
11/15/2010
10:52:29 PM
WD
13.5 mm
mode
SE
HV
20.00 kV
mag
300 x
HFW
853 µm
300 µm
S6-Slice6(IN)

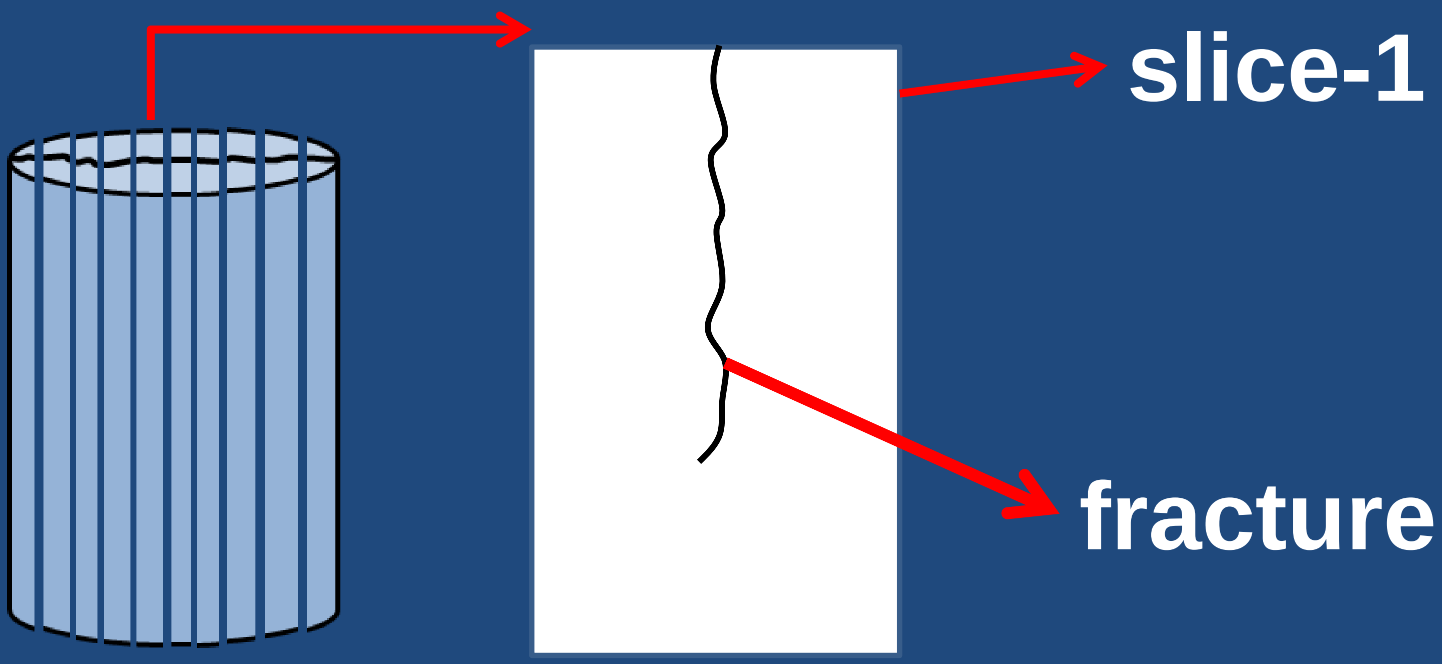

A
0.5 "
Sandstone

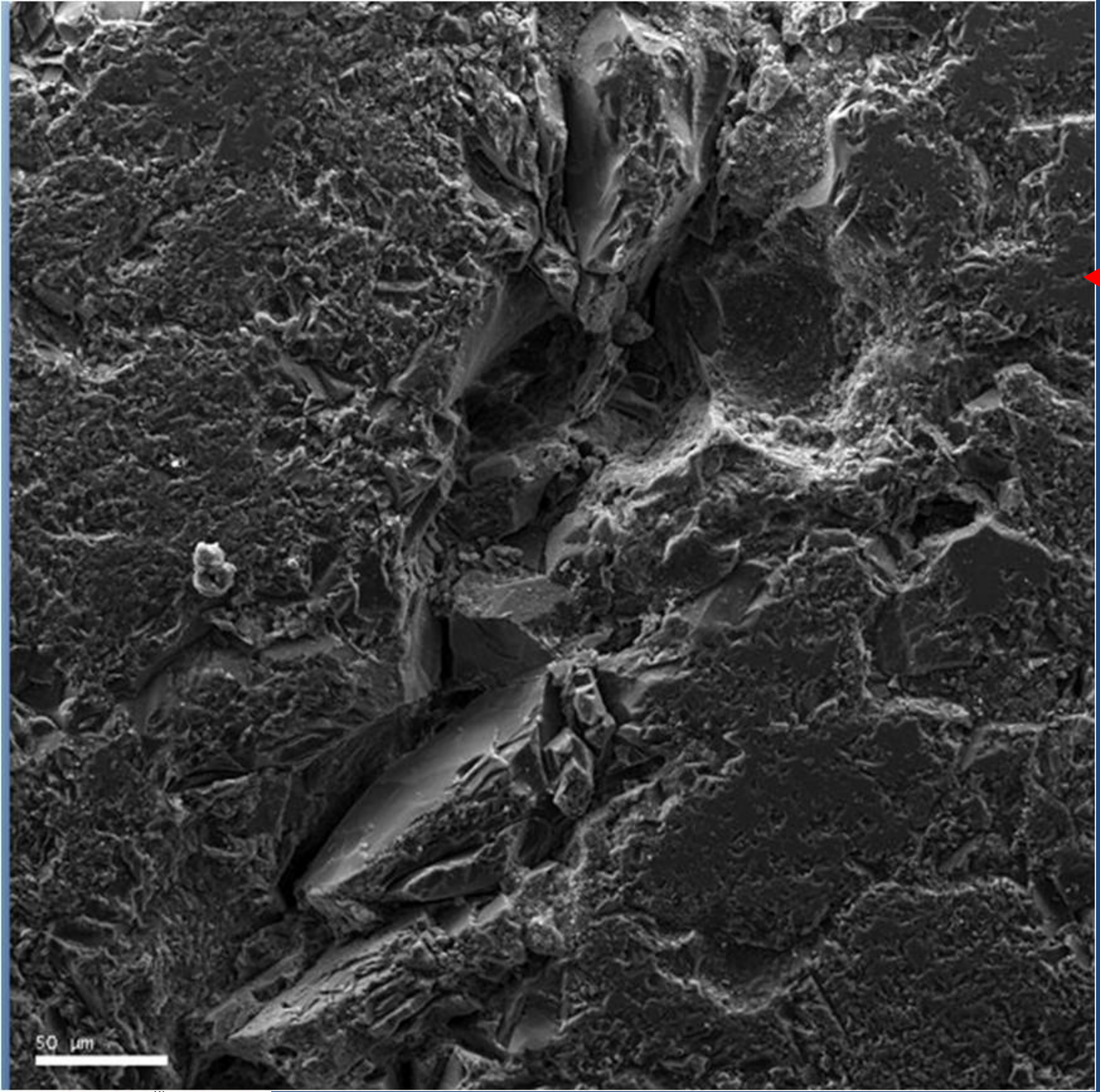

Tensile fracture
5.89µm
4.60µm
85.05µm
Conchoidal fractures
11/15/2010 11:15:58 PM
WD 13.4 mm
mode SE
HV 20.00 kV
mag 600 x
HFW 427 µm
100 µm
S6-Slice6(IN)

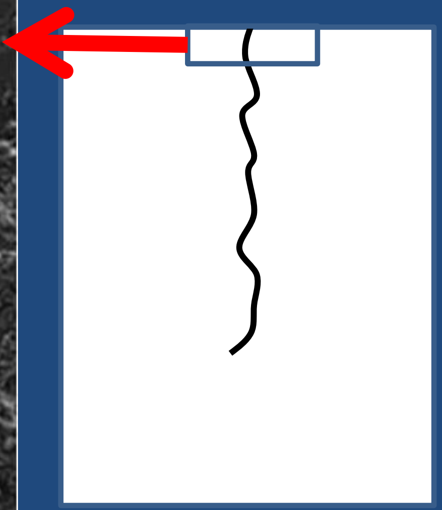

17 mm

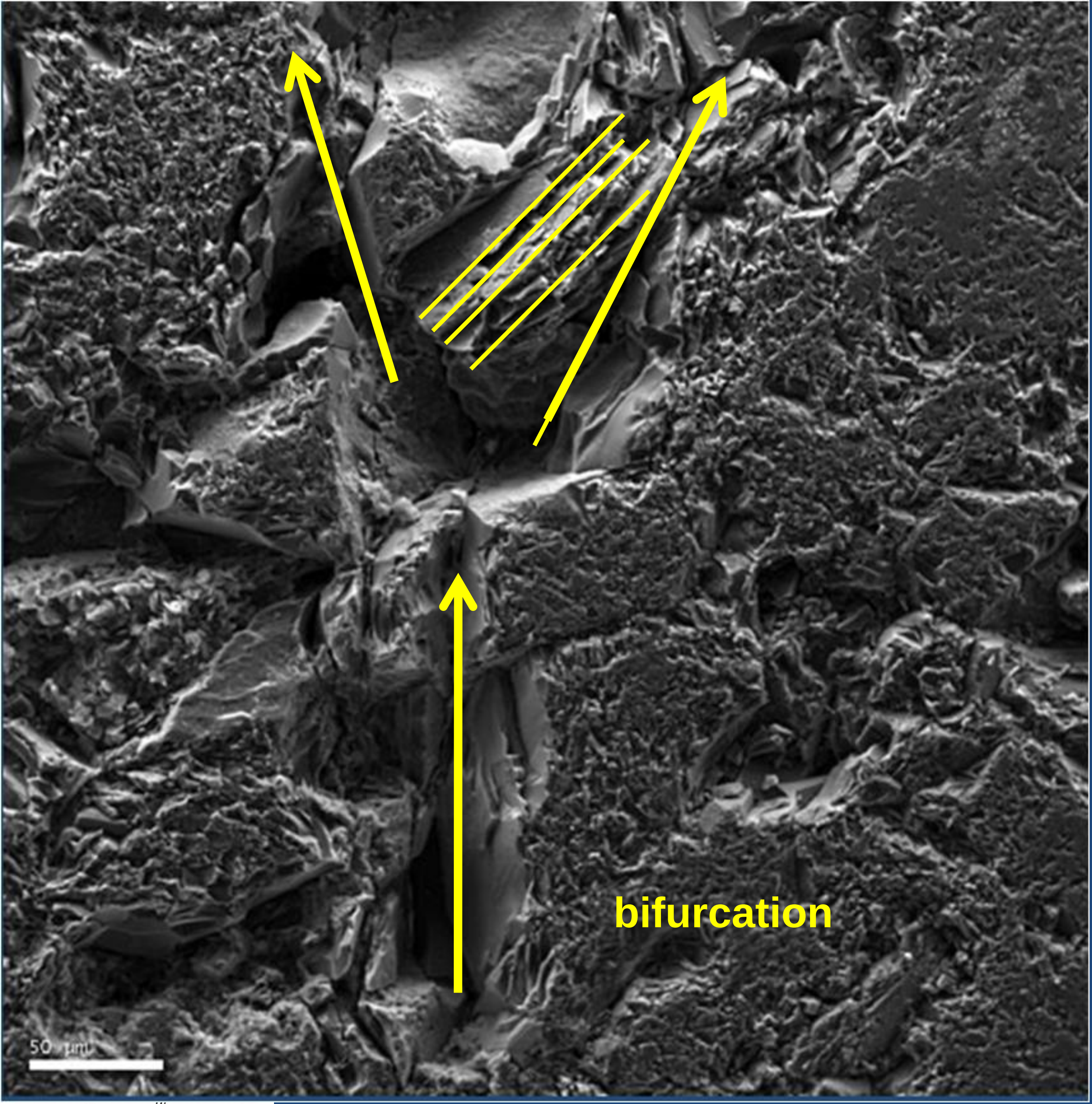

Quartz

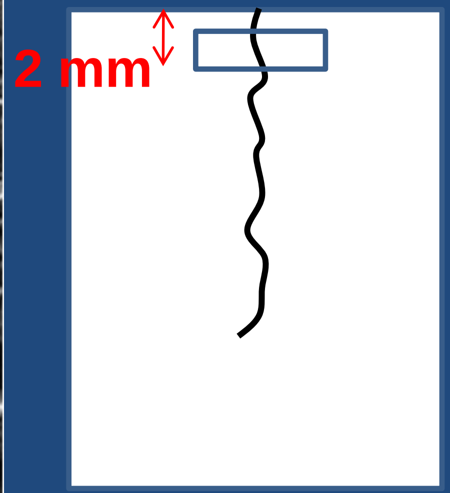
Fracture after propagating 1” from wellbore

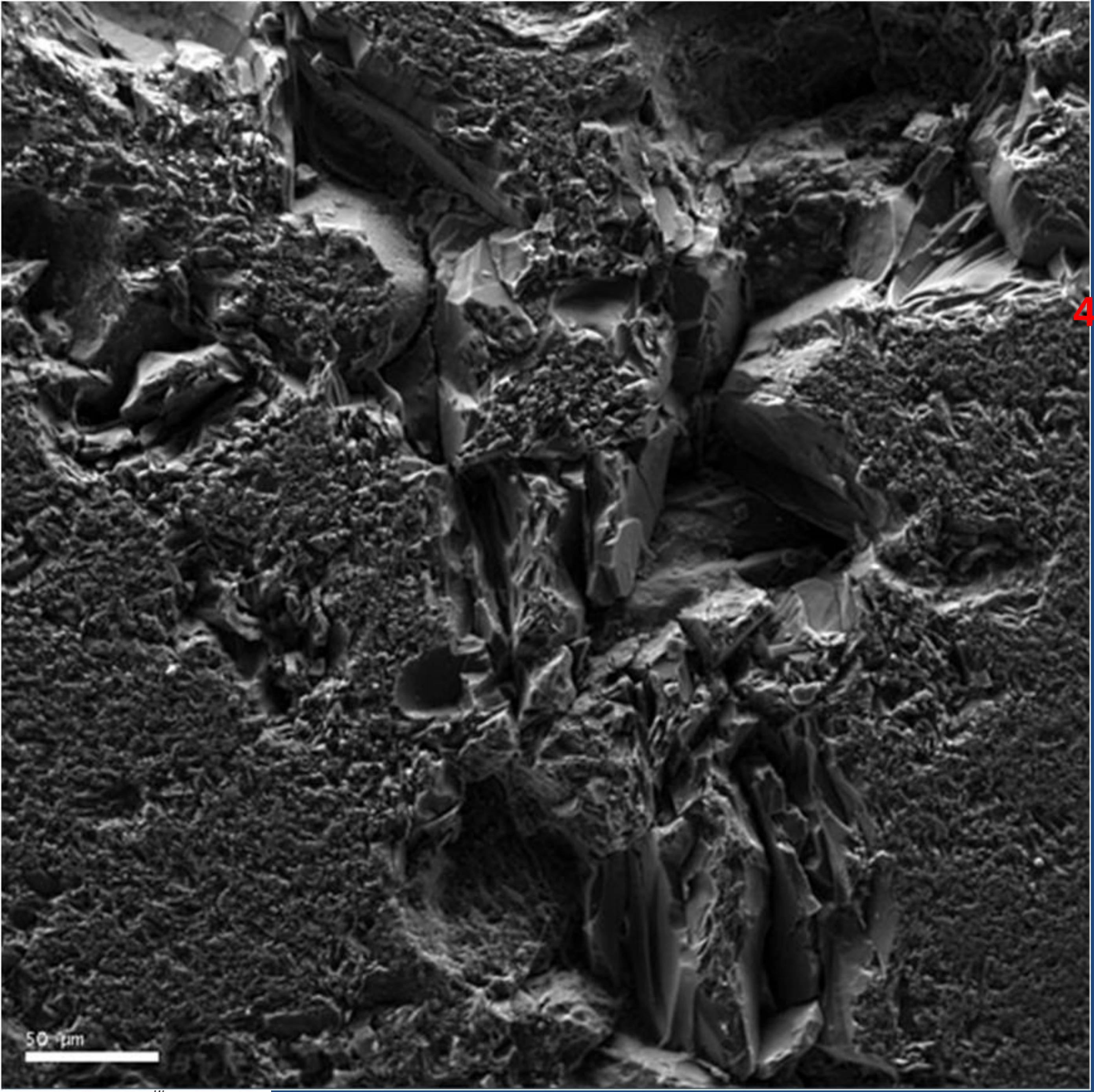


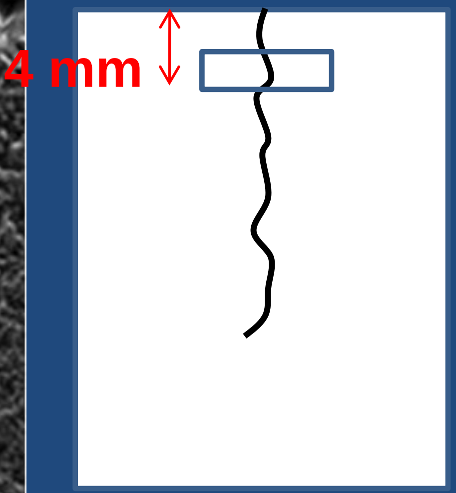

50 µm

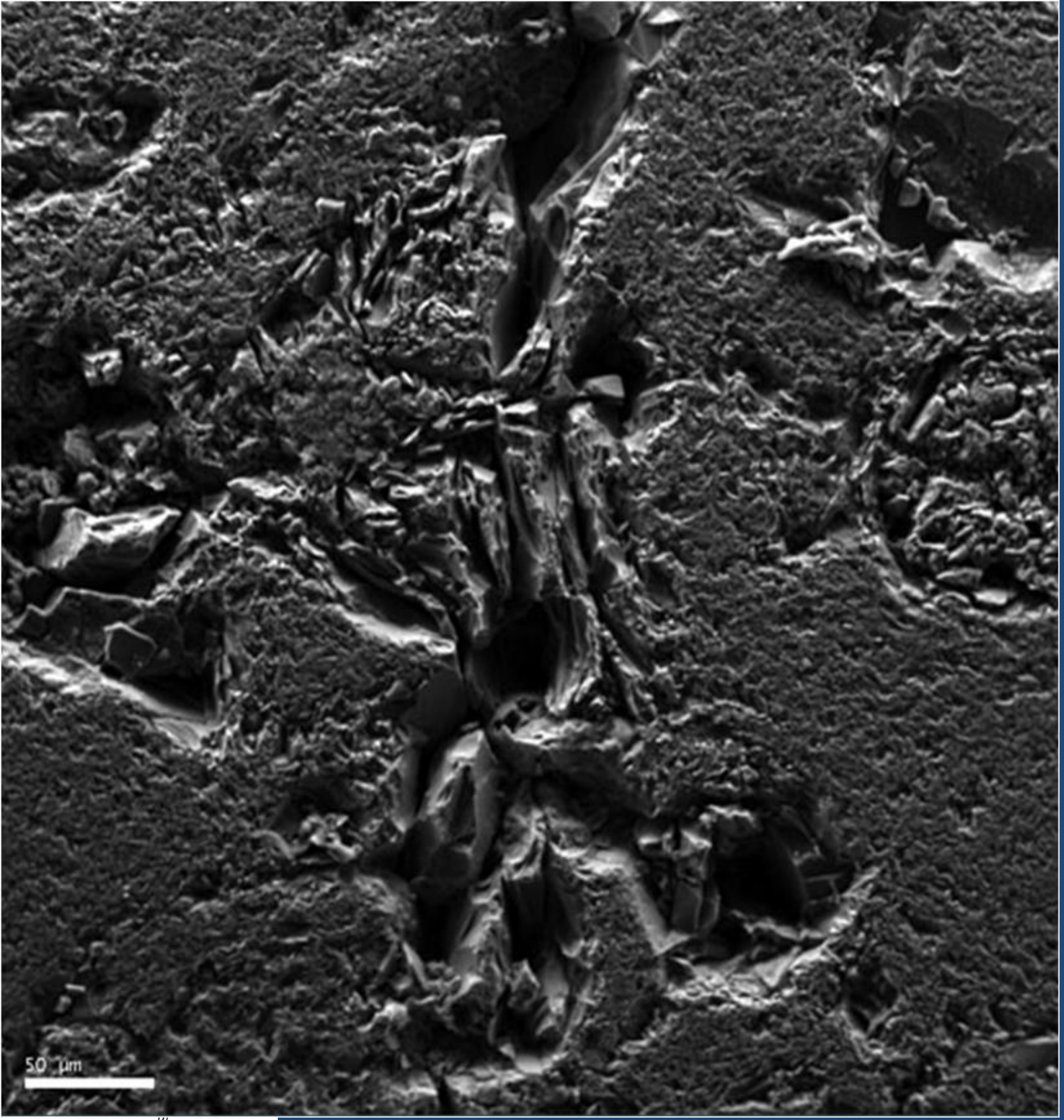


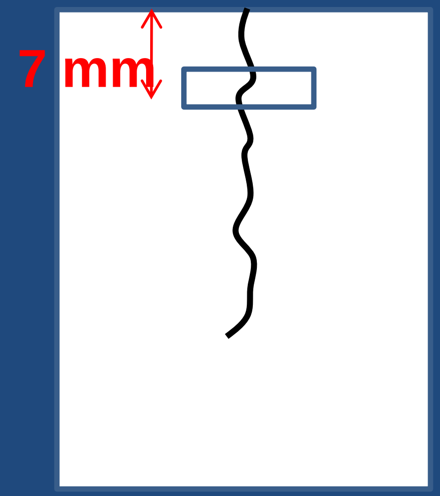

bifurcation
50 μm

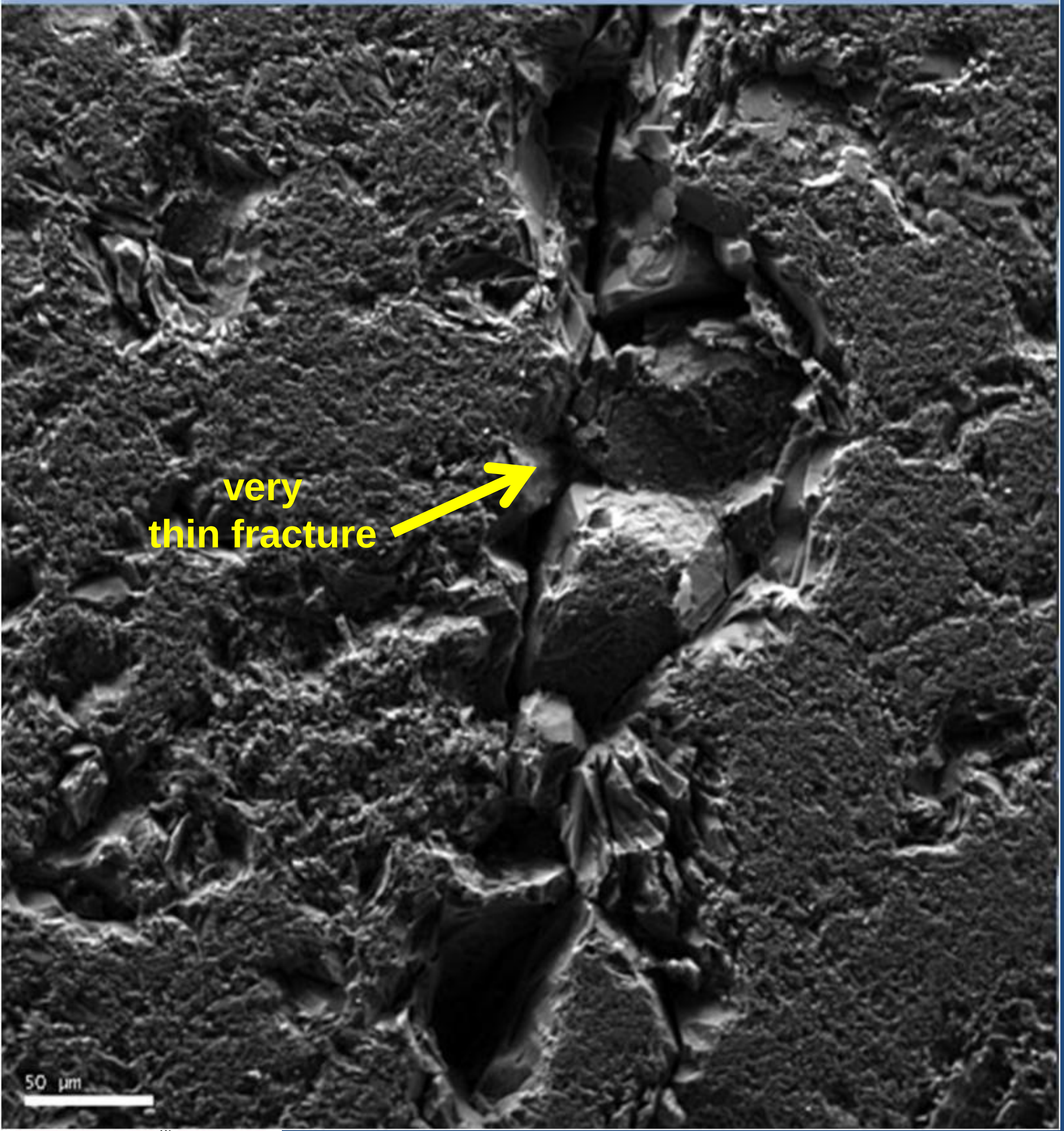

2 mm

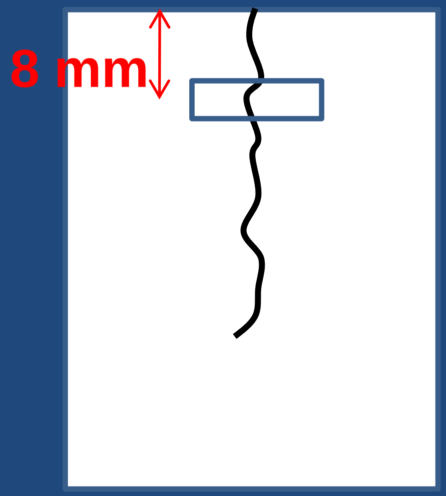

50 µm

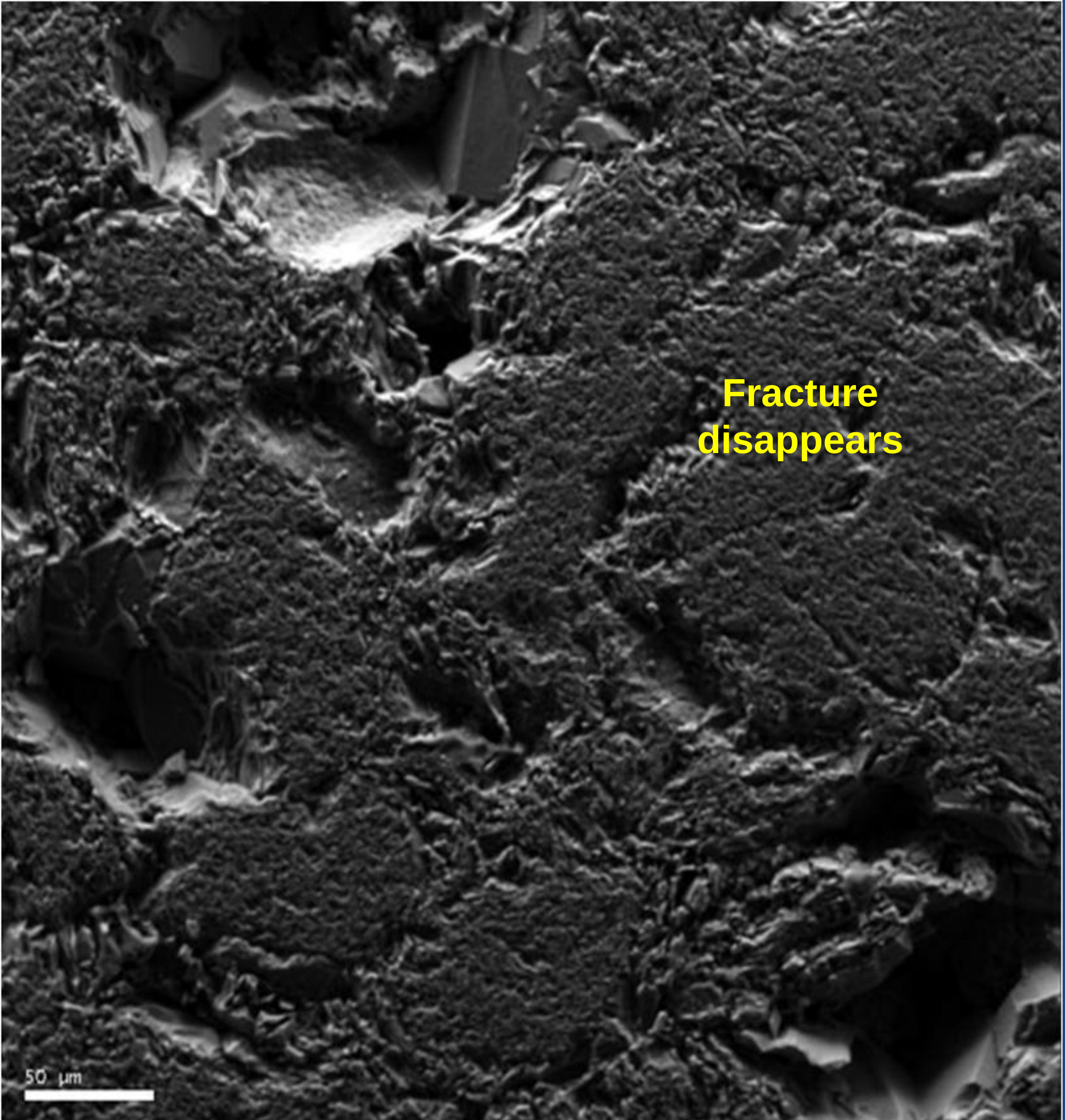

4 mm

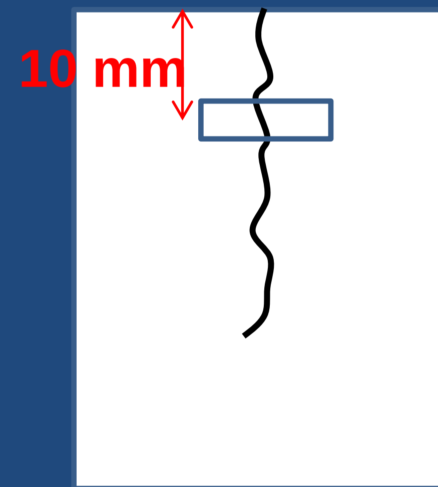

50 µm

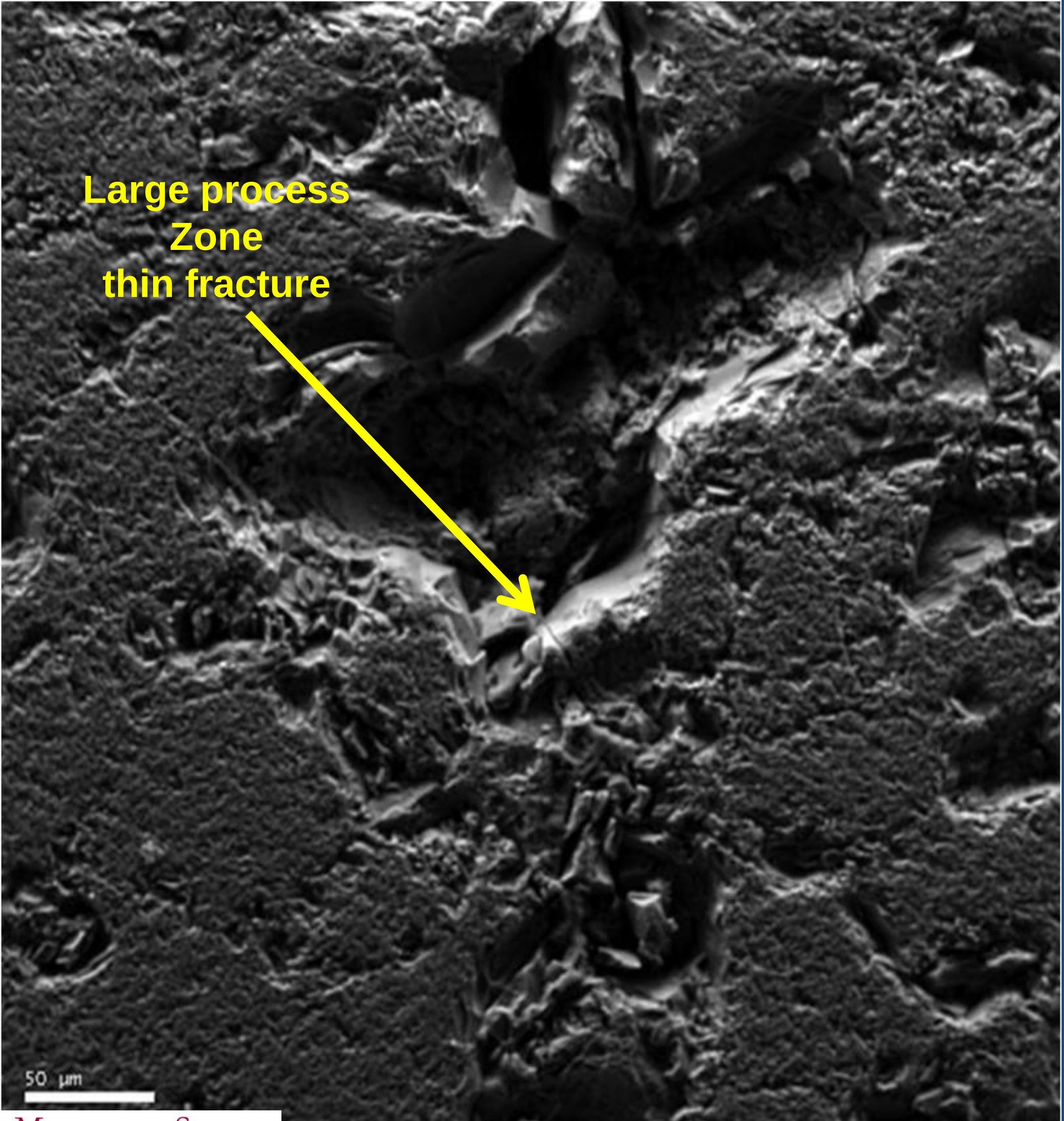

7 mm

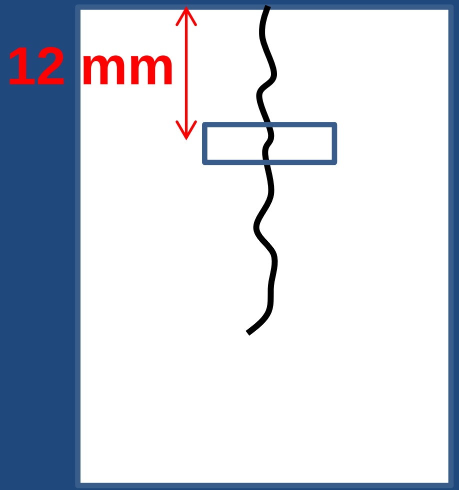

very
thin fracture
50 µm

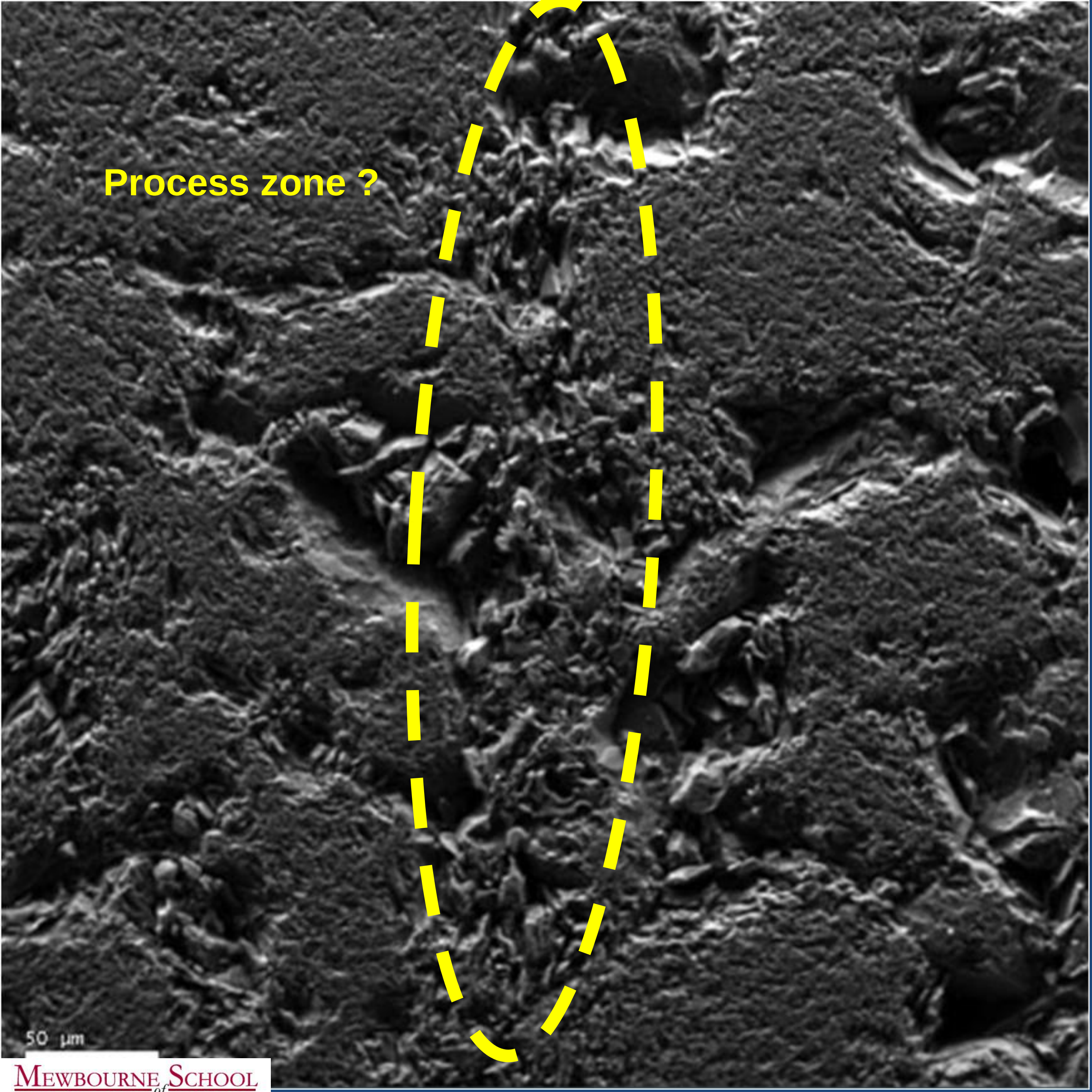

8 mm

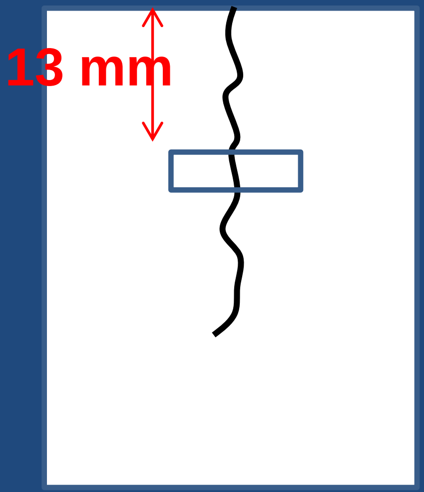

Fracture
disappears
50 μm


10 mm


Large process
Zone
thin fracture
50 µm


12 mm


Process zone ?
50 µm


13 mm

Slice 10

Hydraulic fracturing

- Physical location of fractures agrees with hypocenter locations
- Isotropic materials fractures controlled by applied stress direction
- Anisotropic materials, initiation direction controlled by direction of applied stress and anisotropy
- Shear failure dominates the hydraulic fracture propagation
- MS events correlate with pressure buildup, secondary activity with pump stoppage for brittle lithologies
- Fractures are discontinuous and bifurcate like natural systems
- Fractures are not planar surfaces…controls proppant placement
- Process zone is discontinuous

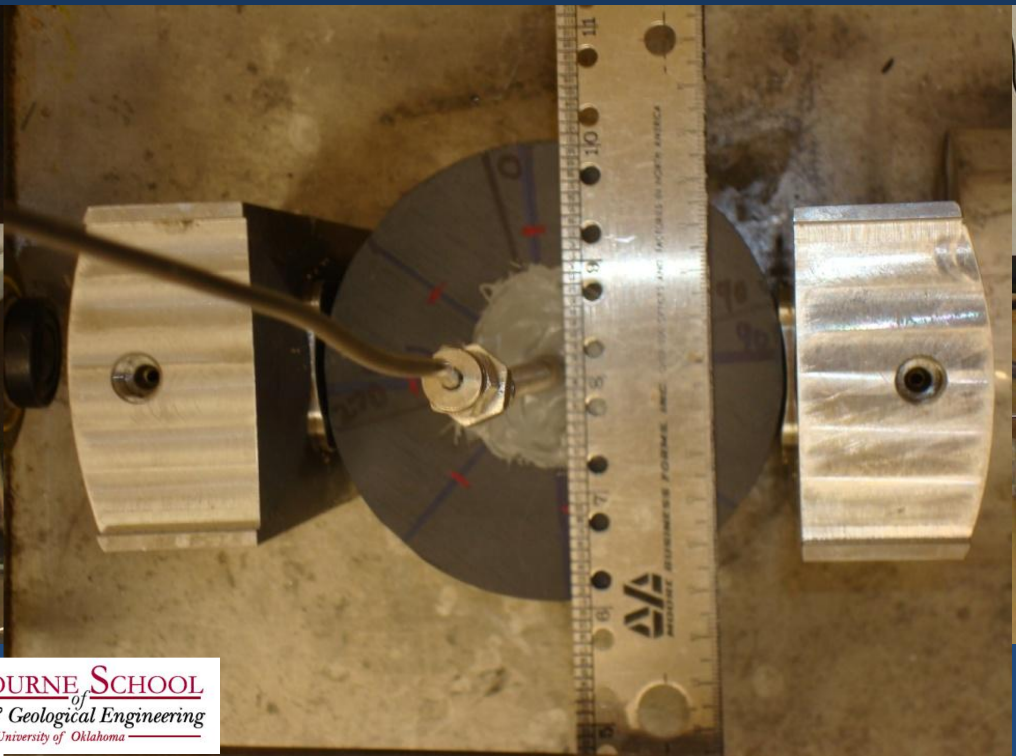
Triaxial Hydraulic Fracture Tests

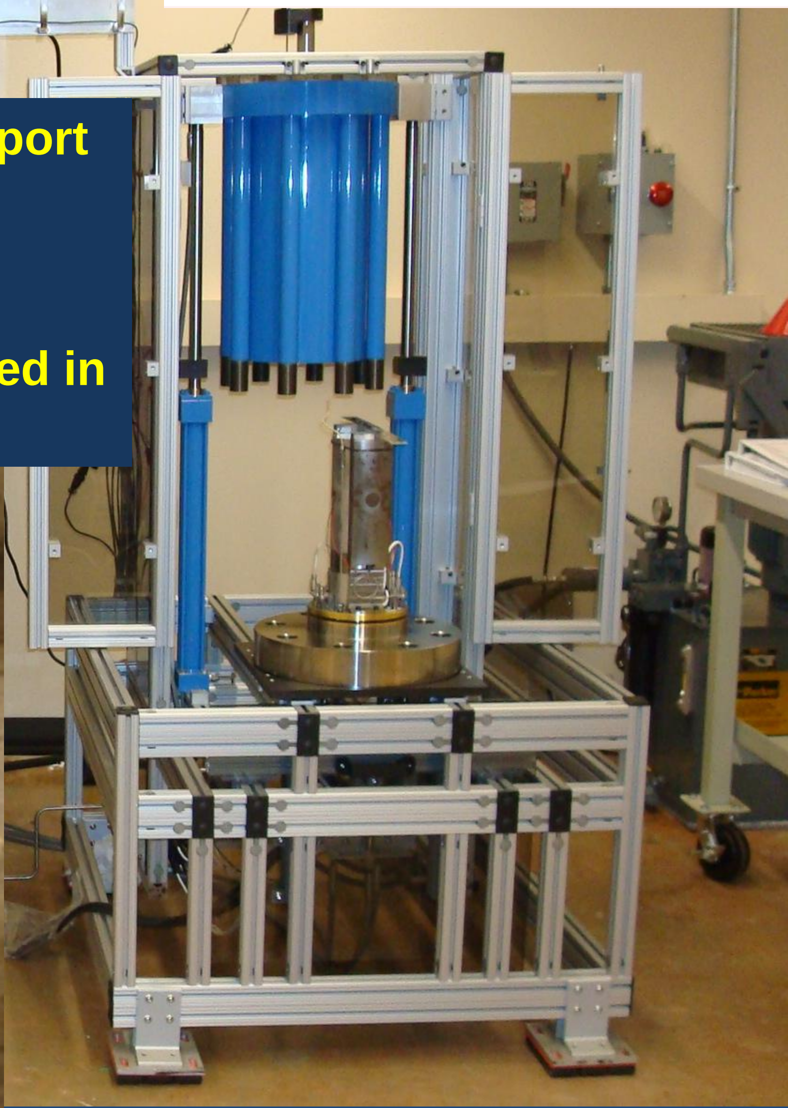
OU - IC 3

We thank Devon Energy for their continued support

Mr. Gary Stowe for his laboratory expertise

Apache and Mewbourne Oil donated the SEM used in these studies





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